WINTER PRECIPITATION HAZARDS IN THE UNITED STATES

by

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(Under the Direction of Thomas L. Mote)

ABSTRACT

Winter precipitation is a significant hazard to lives and property in the United States. This study examines the two main types of indirect fatalities—situations where the winter precipitation leads to a circumstance that causes a death—due to winter precipitation in the United States: vehicle crashes and Carbon Monoxide (CO) poisonings. Over 800 people per year are killed due to winter precipitation related motor vehicle crashes, significantly more than other, prominent weather hazards such as tornadoes. The greatest risk of death due to winter precipitation related crash is found in the Great Lakes, Midwest, and western U.S. While little trend was found in motor vehicle fatalities, aviation fatalities had a significant downward trend, with most aviation fatalities occurring in the high terrain of the western U.S. Analysis of 13 cities finds that property damage, injury, and fatal crash risk increases during winter weather, especially if a reduction in driving is assumed. This risk is greatest during more intense precipitation and across the mid-Mississippi and Ohio River valleys. Finally, fatal CO poisonings related to winter weather induced power outage are examined to determine the characteristics of victims and the geographic extent of these deaths. Most fatalities were among men and those aged 65 or older, with most victims having a high school education or less. Non-Hispanic blacks and non-Hispanic whites are disproportionately affected by winter precipitation power outage related CO poisoning, but Hispanics may be more vulnerable to these events. Spatial analysis of the deaths found that most were in the mid-Atlantic, while states in the Great Plains and Intermountain West that typically see high rates of CO poisonings had no fatalities. Although winter precipitation may not receive much attention from researchers or the general public, it is a hazard which can cause significantly more deaths than other, more prominent, meteorological hazards. It is hoped that this work will provide the groundwork for future research and applications to reduce the risk of winter precipitation and ultimately save lives.

INDEX WORDS: Winter Precipitation, Hazards, Transportation, Climatology, Carbon Monoxide

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DEDICATION

This dissertation is dedicated to my beautiful wife, Michelle. Without your unending love, support, patience, understanding, and encouragement it would not have been possible for me to complete this journey or this document.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

Winter precipitation such as snow, sleet, and freezing rain is a hazard that can have a disruptive effect on human lives. Economic losses from winter storms have been increasing despite a drop in the number of storm events (Changnon 2007). From 1949–2003, there were over 200 storms that caused at least $1 million in damage, with a combined loss of $35.2 billion (Changnon 2007). Winter weather can also cause loss of life in a number of different ways, including vehicle accidents, avalanches, carbon monoxide (CO) poisoning, and individuals slipping and falling on the snow or ice (Eisenberg and Warner 2005, Spencer and Ashley 2011, Spencer 2009). Previous research has estimated that 30–40 (Changnon 2007) or as many as 70 (Borden and Cutter 2008) fatalities a year can be attributed to winter storms in the United States. However, these studies have only considered what are termed as "direct" fatalities, where the storm is a direct agent in the death (NOAA 2007). Examples of direct fatalities would include avalanches and slips and falls. In addition to direct fatalities, winter weather can cause "indirect" fatalities, where the weather creates a situation that leads to the death (NOAA 2007). Indirect fatalities from winter weather can arise from a variety of circumstances, but the two most common are motor vehicle crashes and CO poisonings (Spencer 2009).

The distinction between direct and indirect fatalities is important as *Storm Data,* the publication of the National Weather Service (NWS) that records weather injuries and fatalities, only includes direct fatalities (NOAA 2007). As a result, many previous studies of winter precipitation related mortality in the meteorological literature do not address indirect fatalities which results in an incomplete picture of the threat posed by winter weather. The goal of this study is to examine fatalities caused by vehicle crashes and CO poisonings related to winter precipitation. This research reveals the magnitude of the threat posed by the two largest categories of indirect winter precipitation fatality, facilitating comparison to direct winter weather fatalities and other meteorological hazards. The results of this work are significant for many reasons. While several studies (*e.g.* Spencer and Ashley 2011, Bentley and Haslam 2001, 1998, 1996) have examined direct fatalities, this is the first study to explore indirect fatalities from winter precipitation. This study is also the first to assess traffic accidents, injuries, and mortality due to winter precipitation and compare the results spatially across the United States. Finally, the study examines the overall magnitude of fatal CO poisonings related to winter weather induced power outage, their spatial characteristics across the entire U.S., and determine if the results of previous case studies can be generalized to the country as a whole. Understanding all losses due to winter weather, not just those that are considered direct, is necessary in order to reduce fatalities caused by these events, and the application of the results could lead to a reduction in economic losses, fatalities, and injuries caused by winter precipitation.

1.2 Literature Review

Fatalities related to winter precipitation, whether direct or indirect, are all related to the underlying meteorological processes that produce winter precipitation. For that reason, this literature review will begin by exploring the climatology of winter precipitation. Following this is an examination of research on deaths caused by winter precipitation. Subsequent sections discuss literature on vehicle (automobile and aircraft) crashes and CO poisonings.

a. Climatology of winter precipitation

There are three types of winter precipitation: snow, freezing rain, and ice pellets. Each are formed by similar in-cloud processes, with the resulting precipitation type at the surface being dependent on temperature between the cloud and surface. When a sub-freezing layer exists from the cloud to the ground, snow is the resulting precipitation type. Freezing rain is formed when sub-freezing temperatures exist at the surface with warmer air aloft. Precipitation falls through the warm layer and the resulting liquid freezes on contact with the cold surfaces at ground level (Changnon and Karl 2003). Ice pellets, commonly called sleet, are small, frozen raindrops with diameters less than 5mm, and are formed when precipitation partially or completely melts and re-freezes while falling from the cloud (Changnon 2008).

Changnon et al. (2006) found that snowstorms (defined as an event that produced 15.2 cm of snow or more in 1 to 2 days) were most common across the Rocky and Appalachian Mountains, near the Great Lakes as a result of lake effect snow, and in New England (Fig. 1.1). The seasonality of snowfall is highly dependent on location. Areas of the Rocky Mountains can receive snowfall as early as September and as late as June, while the Deep South may receive snowfall during a much shorter season ranging from December through March (Changnon et al. 2006). Ice pellets are most common across the north central Plains (Fig. 1.2), and occur most frequently in January but can fall anytime between September and May in the High Plains (Changnon 2008), while freezing rain is most frequently found in the Midwest, Northeast, the Appalachians, and parts of the Pacific Northwest (Changnon and Karl 2003; Fig. 1.3). Freezing rain is seen from October through May and is most common in January (Changnon and Karl 2003).

It is expected that the climatology of winter precipitation will change with changing climate. Extreme wet events are expected to increase in the Northwest during winter (December, January, and February), and across the eastern U.S. in spring (March, April, and May), indicating that these regions may experience more winter precipitation in the future (Singh et al. 2013). Most regions are expected to see an overall increase in extremes, with fewer but more intense precipitation events (Singh et al. 2013). Increased numbers of extreme winter precipitation events in the future may lead to increases in economic losses, along with direct and indirect fatalities.

b. Fatalities due to winter precipitation and vulnerability

As previously mentioned, few studies explore fatalities due to winter precipitation and these studies have estimated that as few as 30 (Changnon 2007) or as many as 70 (Borden and Cutter 2008) direct fatalities a year can be attributed to winter storms in the United States. Spencer (2009) found an average of 40 direct fatalities per year due to winter precipitation based on data from 1999–2004 but also note that *Storm Data* is prone to undercounting of direct fatalities. In terms of direct fatalities due to winter precipitation, 27 fatalities per year occur in the U.S. due to avalanches (Spencer and Ashley 2011), while 2–3 fatalities occur per year due to slips and falls (Spencer 2009).

While the presence of winter precipitation is necessary for a fatality to be attributed to winter precipitation, deaths do not simply occur most often in locations that experience frequent winter precipitation or the greatest amount of winter precipitation.

These losses are better understood using the hazards of place framework discussed by Cutter (1996). The overall vulnerability, or potential for loss, for a place is a product of both the vulnerability to the physical hazard and the vulnerability due to societal factors (Cutter 1996). Societal vulnerability includes socioeconomic indicators, cognition of risk, and individual or societal ability to respond to a hazard (Cutter 1996). In terms of winter precipitation, this could include the perception of the risk that motorists face when driving during winter weather, or the ability of society to respond to winter weather through snow removal. Physical vulnerability includes the site, situation, and proximity of a particular place to a hazard. In this research, physical vulnerability is primarily related to the climatology of winter weather. As the climatology of winter precipitation changes under changing climate, both the physical and societal vulnerability will also change. For example, more intense snowfall increases physical vulnerability due to amount of snow that falls, but can also increase societal vulnerability by taxing snow removal systems. Therefore, it is of critical importance to assess fatalities due to winter precipitation in order to understand how both physical and societal vulnerability may contribute to these deaths and the effect that changing vulnerability will have in the future.

c. Vehicle crashes

Vehicle crashes were the largest contributor to indirect fatalities identified by Spencer (2009). While several studies have explored automobile crashes due to winter precipitation, most have been focused on crash rates, primarily in Canada. One U.S. study examined crash rates in aggregate for the entire U.S., but did not look at total fatalities or examine the results spatially. The following sections explore previous research on winter precipitation motor vehicle and aircraft crashes.

i. <u>Automobile crashes</u>

In 2010, the World Health Organization declared 2011–2020 the "Decade of Action for Road Safety" in response to the enormous toll that roadway crashes take on individuals, communities, and national economies (WHO 2013). In 2010, 1.24 million people were killed on the world's roads (WHO 2013). In the United States, nearly 33,000 fatalities and 2.2 million injuries occurred due to motor collisions in 2010 (NHTSA 2011). In the U.S., snowfall leads to an additional 45,000 additional injury-causing crashes and 150,000 property damage crashes per year relative to what would be expected if those days were dry (Eisenberg and Warner 2005).

Since the early 1970s, several studies have examined winter precipitation and its influence on motor vehicle crashes; Table 1 of Andrey et al. (2003) lists a number of studies conducted from the 1970s through the early 2000s. More recent work has examined trends in weather related crash risk, driver adaptation, and collision and injury risk in Canada (Andrey 2010; Andrey et al. 2013; Mills et al. 2011) and the effects of snowfall on collisions, injuries and fatalities in the U.S. (Eisenberg and Warner 2005). These studies consistently demonstrate that risk of both collision and injury are significantly elevated during winter precipitation. Meta-analysis of 34 studies on weather and traffic crashes by Qiu and Nixon (2008) found that snowfall can increase the crash rate by 84% and the rate of injury by 75%, while fatality rates only increased 9% after accounting for reductions in traffic volume. Eisenberg and Warner (2005) found that snowfall days had fewer fatal crashes with the exception of the first snowfall of the year, which had an elevated fatality rate, especially in the elderly. However, an 18% increase in fatality rate was found after adjustment for reduced traffic volume during snowfall days (Eisenberg and Warner 2005).

Available research suggests that driver responses are insufficient to completely offset the risk of driving in weather conditions, which make vehicle handling more difficult, reduce traction, or reduce visibility, which leads to increases in crash rates (Andrey et al. 2013, Eisenberg and Warner 2005). The magnitude of the increase in crash rates depends physical vulnerability factors such as weather conditions (e.g. precipitation type or intensity), time of day, and societal vulnerability factors such as previous experience with winter precipitation. In a study of 23 Canadian cities, Andrey et al. (2013) found that drivers do not become acclimated to or experience reduced risk of crash during frequently experienced environmental conditions. Further, drivers are less likely to reduce speed in rural areas or areas with higher posted speed limits during both rainfall and snowfall, increasing crash risk as compared to urban areas or areas with lower speed limits (Andrey et al. 2013). Finally, Andrey (2010) found no discernible trend in relative risk (the probability of an event occurring in an exposed group compared to a non-exposed group) of crash due to snowfall in 10 Canadian cities during the period 1984–2002, indicating that casualty rates due to snowfall declined in ways consistent with the overall trend of decreasing vehicle collisions.

ii. Aircraft crashes

Aviation is also vulnerable to the effects of winter precipitation in several ways. During takeoff and landing, aircraft can slide off of runways that are wet or have accumulated slush, snow, or ice. A study of European aviation found that operating in these runway conditions leads to a four-fold increase in the accident risk (van Es et al. 1998). Another hazard is loss of control in flight due to winter precipitation. Analysis of commercial aviation loss of control accidents from 1979–2009 revealed two chains of events related to winter weather (Belcastro and Foster 2010). One chain involved snowfall reducing visibility, while the second chain involved accumulation of ice or snow on aircraft control systems (Belcastro and Foster 2010). Belcastro and Foster (2010) found that both chains led to an eventual loss of control of the aircraft through some combination of mechanical failure, inappropriate crew response, or aircraft upset (unintentionally exceeding parameters experienced during operations).

d. CO poisonings

CO poisonings were the second largest contributors to indirect fatalities identified by Spencer (2009). Winter precipitation and bitter cold can disrupt critical infrastructure such as electrical power. In most cases loss of electrical power will result in no deaths, but outages which are larger in size, longer in duration, or that coincide with other hazardous events can lead to fatalities (Yates 2013). Three death modes or chains of events involving CO poisoning after electricity loss were identified by Yates (2013): loss of electricity supply resulting in generator use, loss of electricity leading to use of an alternative combustion-based heating method, and loss of electricity leading to use of an alternative combustion-based cooking source. In each of the three cases, the initial power loss and subsequent actions lead to an indoor build-up of CO which then leads to CO poisoning (Yates 2013).

Carbon monoxide is a colorless, odorless, and tasteless gas formed due to the incomplete combustion of carbon-based fuels (Johnson-Arbor et al. 2014). Mild exposure to CO can cause flu-like symptoms including fatigue, nausea, vomiting, headache, dizziness, and confusion, while prolonged exposure can cause serious effects such as collapse, coma, cardiorespiratory failure and death (Iqbal et al. 2012b). Many studies have shown that disruptions of electrical power due to winter weather can lead to CO poisoning following sequences of events described by Yates (2013). Iqbal et al. (2012a) reviewed 28 journal articles on CO poisoning from disasters such as hurricanes, winter storms, and flooding and found that most victims were male and over 18 years of age. Generators were the source of CO for over 75% of the fatal incidents, with propane, kerosene, or gas-fueled heaters acting as the CO source in 10% of fatal incidents (Iqbal et al. 2012a). Charcoal grills were the source for the remaining 15% of fatal CO incidents, with these primarily occurring after winter storms (Iqbal et al. 2012a). Fatal CO poisonings were most common within three days of the disaster onset – 9% of cases occurred on the day of the event, 22% on the day after the event, and 43% on the third day after the event (Iqbal et al. 2012a).

Case studies that focused exclusively on CO poisonings after winter precipitation such as snowfall or freezing rain found similar results to Iqbal et al. (2012a). Portable generators were the most common CO source, followed by charcoal grills after storms that caused power loss in Connecticut (Johnson-Arbor et al. 2014; Styles et al. 2014) and Maine (Daley et al. 2000). In both studies, most cases of CO poisoning were reported one to four days after the storm, with the second and third day having a large spike in cases as compared to days one and four (Johnson-Arbor et al. 2014; Daley et al. 2000). In at least one study of winter weather related CO poisonings, racial and ethnic minorities and those with English as a second language were the majority of poisoning victims

(Styles et al. 2014). Required pictorial labels to warn of CO poisoning on charcoal and generators were not often seen by victims in Connecticut (Styles et al. 2014) and the labels were only correctly interpreted 74% of the time, falling short of the 85% level recommended by the American National Standards Institute (ANSI) (Styles et al. 2014).

Daley et al. (2000) found that running a generator in a structure attached to the home made it 19 times more likely that someone within the house would be a victim of CO poisoning, while running the generator in the basement made CO poisoning 300 times more likely. Residents chose to operate generators in these locations for several reasons including weather, concerns of theft, and length of extension cords (Styles et al. 2014). Several CO poisoning prevention strategies are suggested by the literature, including educational campaigns (Johnson-Arbor et al. 2014), public service campaigns, including the use of social media, before and after major storms (Johnson-Arbor et al. 2014; Styles et al. 2014; Daley et al. 2000), improved warning labels (Styles et al. 2014), and the use of multi-lingual warnings based on local population (Styles et al. 2014).

1.3 Research Questions

The first manuscript (Chapter 2) examines the spatial and temporal characteristics of fatal vehicle crashes—one type of indirect fatality—that involve winter precipitation for the period 1975–2011. The study examines motor vehicle and aircraft crashes, two types of transportation accidents that commonly occur during winter precipitation. In addition, the manuscript compares fatalities from these crashes to other meteorological hazards. The manuscript addresses the following questions:

- What are the temporal characteristics of fatal motor vehicle crashes related to winter precipitation, and how does this compare to non-winter related fatal crashes?
- How does expected mortality from these crashes vary spatially, and do clusters exist that might indicate increased or decreased vulnerability to these crashes?
- What are the spatial and temporal characteristics of fatal winter precipitation related aviation crashes?
- How do fatality counts from these indirect winter weather causes compare to fatalities from direct causes and to other meteorological hazards?

The second manuscript (Chapter 3) explores the relative risk of automobile crash during winter precipitation events for 13 U.S. cities based on data from 1996-2010 by comparing the number of fatal, injury, and property damage only crashes during winter precipitation to the number of crashes during control periods. The following questions will be examined in this manuscript:

- What is the aggregate relative risk of crash during winter precipitation based on the 13 study cities?
- What are the spatial patterns of the relative risk of vehicle collision, injury, or fatality during winter precipitation in the U.S.?
- How do factors such as precipitation type (snow vs. freezing rain and sleet), precipitation intensity, time of day, and being the first winter precipitation event of the year influence relative risk of crash?
- What is the trend in relative risk?

Finally, the third manuscript (Chapter 4) examines fatal CO poisonings that are related to power outages created by winter precipitation for the years 1984–2004. Using data on power outages, significant snowstorms, and fatal CO poisonings, the study examines the following questions:

- Are the results of previous case studies on CO poisonings related to winter weather generalizable to the entire U.S.?
- What is the overall magnitude of the threat to public health due to these events?
- What are the demographic characteristics of the victims?
- What are the spatial patterns of mortality?

1.4 Summary

The true risk posed by winter precipitation is currently difficult to quantify, as many of the fatalities result from indirect causes, and no studies have examined indirect fatalities due to winter weather. The distinction between direct and indirect fatalities due to winter precipitation has resulted in an underestimation of the number of deaths caused by these events in the U.S. This study will quantify fatalities due to two of the largest causes of indirect winter precipitation related mortality – vehicle accidents and CO poisonings. The first part of this dissertation will explore the statistical and spatial components of vehicle fatalities caused by winter precipitation. This is significant as it will reveal areas that may be more or less vulnerable to these events, and provide quantification of the number of deaths caused by this indirect winter precipitation hazard.

Secondly, this dissertation will further explore the risk to motorists by quantifying the actual risk of traveling during winter weather based on 13 U.S. cities. Beyond examining meteorological factors that may influence this risk, the study will also examine how the risk varies across the U.S. There are several potential implications for this information, but understanding the patterns of risk can lead to more effective interventions to improve roadway safety during winter precipitation.

Finally, this dissertation will explore fatal CO poisonings that result from power outages due to winter weather, another significant cause of indirect winter precipitation related deaths. This will be the first study to explore these deaths in aggregate across the entire U.S., and information about demographics and locations of victims may lead to improved safety information and reduced fatalities in the future. Overall, it is hoped that this research will improve our understanding of losses caused by winter weather and that this knowledge will be applied to reduce these losses in the future.

CHAPTER 2

CHARACTERISTICS OF WINTER PRECIPITATION RELATED TRANSPORTATION FATALITIES IN THE UNITED STATES[1]

[1] Black, A.W. and T.L. Mote, 2015: Characteristics of Winter Precipitation Related Transportation Fatalities in the United States. *Weather, Climate, and Society*, in press. doi: 10.1175/WCAS-D-14-00011.1 ©American Meteorological Society. Used with permission.

ABSTRACT

Winter precipitation can be very disruptive to travel by aircraft and by motor vehicles. Vehicle fatalities due to winter precipitation are considered “indirect” and not counted in Storm Data, the publication commonly used to evaluate losses from meteorological hazards. The goal of this study is to examine the spatial and temporal characteristics of these “indirect” transportation fatalities that involve winter precipitation for the period 1975–2011. Motor vehicle fatalities were gathered from the National Highway Traffic Safety Administration's (NHTSA) Fatality Analysis Reporting System (FARS) database, while aviation fatalities were collected from the National Transportation Safety Board’s (NTSB) Aviation Accident Database. Statistical analysis and Geographic Information Systems (GIS) were used to assess the spatial and temporal characteristics of these deaths. Most winter precipitation related motor vehicle fatalities occur during the daylight hours. Fatal motor vehicle accident rates are higher than expected in the Northeast and Great Lakes regions, while winter precipitation related aviation fatalities are most common in the western U.S. Vehicle fatality counts due to winter weather are compared to fatality counts for various hazards from Storm Data to highlight the differences between datasets. Due to the exclusion of vehicle fatalities, Storm Data underestimates by an order of magnitude the number of fatalities which involve winter weather each year. It is hoped that a better understanding of winter precipitation mortality can be applied in order to reduce fatalities in the future.

2.1 Introduction

Winter precipitation such as snow, sleet, and freezing rain is a hazard that can have a disruptive effect on human lives. One of the greatest impacts of these storms is on travel by both vehicles and aircraft. Poor road conditions and reduced visibility during winter precipitation can lead to motor vehicle collisions, while reduced visibility or flight through winter precipitation can lead to aircraft crashes. Previous research has estimated that 30–40 (Changnon 2007) or as many as 70 (Borden and Cutter 2008) fatalities a year can be attributed to winter storms in the United States. However, these studies have only considered what are termed as “direct” fatalities, where the storm is a direct agent in the death (NOAA 2007). An example of a direct fatality would be someone slipping on a snowy sidewalk and sustaining a fatal head injury. However, a much larger number of winter precipitation fatalities are “indirect,” where the weather created a situation that led to the death (NOAA 2007). This distinction is important as *Storm Data*, the publication of the National Weather Service (NWS) that records weather injuries and fatalities, only includes direct fatalities (NOAA 2007). As a result, many previous studies of winter precipitation mortality in the meteorological literature do not address indirect fatalities and therefore exclude a significant number of fatalities, which results in an incomplete picture of the threat posed by winter weather.

The goal of this study is to examine the spatial and temporal characteristics of fatal vehicle crashes—one type of indirect fatality—that involve winter precipitation for the period 1975–2011, similar to recent studies of direct fatalities due to other meteorological hazards such as tornadoes (Ashley 2007), lightning (Ashley and Gilson 2009), nonconvective wind (Ashley and Black 2008) or thunderstorm wind (Black and

Ashley 2010). After sections on background (Section 2) and methodology used (Section 3), this study examines two types of transportation accidents that commonly occur during winter precipitation – motor vehicle (Section 4a) and aircraft crashes (Section 4b). In addition, this study highlights differences between mortality datasets by comparing fatalities due to motor vehicle and aviation crashes to mortality information from *Storm Data*, most notably the dissimilarity of fatality counts between the two datasets (Section 4c). Reduction of mortality due to winter precipitation requires an understanding of both direct and indirect fatalities. The results of this study provide a more complete picture of the hazard posed by winter precipitation to motorists across the U.S., which can then be used to guide efforts to reduce these fatalities in the future.

2.2 Background

While winter precipitation is one of many factors that could lead to a crash, the risk of motor vehicle crashes increases greatly when snow or ice is present despite reduced traffic volumes and reduced vehicle speed (Andrey et al. 2003). Snowfall across the United States leads to an additional 45,000 vehicle collision injuries and 150,000 property damage vehicle collisions per year as compared to dry days (Eisenberg and Warner 2005). In addition, Andrey (2010) notes that the relative risk of collision during any type of precipitation is similar to the risk of being responsible for a collision while under the influence of alcohol with a blood alcohol content of 0.08 relative to no influence of alcohol. A more modest increase in vehicle collision *fatalities* can be attributed to snowfall, with an additional 30 fatal vehicle crashes per year, occurring primarily during the first snowfall of the year (Eisenberg and Warner 2005). Subsequent snow days had fewer fatal crashes, but more overall crashes, and more injuries than days with no precipitation (Eisenberg and Warner 2005). The vulnerability of motorists to winter precipitation was not uniformly distributed, with elderly drivers having the highest risk for a fatal crash during the first snow of the year, while subsequent snowfalls increased the risk of fatal crashes for drivers aged 30–50 (Eisenberg and Warner 2005). After comparing six cities across Canada, Andrey et al. (2003) found that precipitation is associated with a 75% increase in traffic collisions and a 45% increase in injuries. Further, snow related collisions have different characteristics than those that do not involve precipitation (Andrey et al. 2003). Snowfall related collisions are more likely to occur at night, on gradients or curved sections of roadway, and tend to be less serious than crashes occurring under normal driving conditions (Andrey et al. 2003). Additionally, snow-related collisions are more likely to involve only one vehicle, occur on rural roads, and on roads with speed limits of 60 km hr^{-1} or higher (Andrey et al. 2003). Collisions involving snow are less likely to occur at intersections or during a turning maneuver than collisions during normal driving (Andrey et al. 2003).

Aviation is also vulnerable to the effects of winter precipitation in several ways. During takeoff and landing, aircraft can slide off of runways that are wet or have accumulated slush, snow, or ice. A study of European aviation found that operating in these runway conditions leads to a four-fold increase in the accident risk (van Es et al. 1998). Another hazard is loss of control in flight due to winter precipitation. Analysis of commercial aviation loss of control accidents from 1979–2009 revealed two chains of events related to winter weather (Belcastro and Foster 2010). One chain involved snowfall reducing visibility, while the second chain involved accumulation of ice or snow on aircraft control systems (Belcastro and Foster 2010). Belcastro and Foster (2010) found that both chains led to an eventual loss of control of the aircraft through some combination of mechanical failure, inappropriate crew response, or aircraft upset (unintentionally exceeding parameters experienced during operations). This study will build on existing research to determine the spatial and temporal characteristics of winter weather related transportation fatalities. Fatalities from these accidents are considered to be "indirect" and are traditionally omitted from analysis by the meteorological community. It is hoped that this research will reveal patterns of vulnerability, which can then be used to develop more effective intervention strategies to reduce fatalities due to winter weather.

2.3 Methodology

Information on fatal vehicle crashes in the conterminous U.S. was gathered from the National Highway Traffic Safety Administration's (NHTSA) Fatality Analysis Reporting System (FARS) for the years 1975–2011. Created in 1975, the FARS database catalogs information on any motor vehicle crash that results in the death of any person (vehicle occupant or non-occupant) within 30 days of the crash (NHTSA 2012). Data on the crashes are gathered from various sources, including police reports, death certificates, vehicle registrations, and vital statistics, among others (NHTSA 2012). These documents are analyzed and coded into the data elements within the FARS. To isolate the fatalities that were related to active winter precipitation, each annual FARS file was searched for coded weather variables that indicate the weather at the time of the crash. Fatalities which involved winter precipitation were coded as sleet (code 3) or snow (code 4), and these were extracted from the FARS data for further analysis. Since the focus of this study is on collisions that occur during winter precipitation rather than crashes that are related to winter weather as a whole, this approach intentionally limits the results to crashes where winter precipitation was occurring at the time of collision.

As expected, most fatalities occur during the winter season, roughly October through April, although winter precipitation can fall in high terrain as early as September or as late as May. Initial analysis of the number of fatalities by month revealed several winter weather related fatalities in the summer months of June, July, and August. Fatalities occurring within the months of May through September were further analyzed to determine if they were truly a result of winter precipitation or if the weather conditions were possibly coded in error. To make this determination, daily cooperative weather data for each station within a county that saw a fatality during the May through September period were examined to determine if snowfall occurred or if below freezing temperatures were observed in conjunction with precipitation. If snowfall or precipitation with below freezing temperatures were not observed, the event was excluded from the database. Overall, this led to the exclusion of 132 events, or 0.5% of the original data.

Data on fatal aircraft accidents in the conterminous U.S. was gathered from the National Transportation Safety Board's (NTSB) Aviation Accident Database for the years 1975–2011 (NTSB 2013). The NTSB database contains information about aviation accidents from 1962 to present and lists the circumstances and cause of the each accident. These data were gathered by searching the database for events with one or more fatalities where the accident narrative contained keywords associated with winter precipitation such as "snow," "sleet," "freezing rain," "slid off runway," or "icing." For each event, the accompanying narrative was read to determine if winter precipitation was involved in the accident, and if so, the event was included for further analysis. Initial analysis found two main causes of these accidents. The first cause was an encounter with winter precipitation during some phase of flight, while the other cause was ice accumulation on aircraft control surfaces. Because icing can occur anytime an aircraft encounters supercooled water droplets (Rasmussen et al. 1992) and is not necessarily related to winter precipitation, the accident narrative for each crash was read to ensure only those caused by winter precipitation were included in the study.

Fatalities for both motor vehicle and aviation events were aggregated by counties due to a lack of more precise location data within the motor vehicle crash data; for 1975–2003, only 30% of fatal motor vehicle crashes had geographic data beyond state and county. A geographic information system (GIS) was used to display the spatial patterns of these events and fatalities. All maps were projected using the Lambert Conformal Conic projection to preserve shape.

Mortality rates were calculated to explore the effect of population on the spatial pattern of fatalities and to compare the expected number of deaths that involve winter precipitation to the actual number of deaths that were observed. Age-adjusted death rates were calculated using direct standardization techniques based on winter precipitation related motor vehicle fatalities and the population by age group within each state (Wilson and Buescher 2002). Using the calculated age-adjusted death rates, the expected number of winter precipitation related motor vehicle fatalities for each county was determined (Wilson and Buescher 2002). The standardized mortality ratio (SMR) was then calculated for each county by dividing the observed number of fatalities by the expected number of fatalities. The SMR is a commonly used measure of mortality in spatial epidemiology research (Borden and Cutter 2008; Wilson and Buescher 2002). SMR values greater than one indicate that the death rate in a particular area was higher than that of the standard population, while values less than one indicate the rate in the particular area was lower than that of the standard population (Wilson and Buescher 2002). The SMR is sensitive to population size, with large variance of the SMR found in areas with small population and small variance in areas with large population (Meza 2003). In the extreme, when the expected fatalities are close to zero, the SMR will be very large for any positive count of actual fatalities (Lawson 2001). Counties with small populations see larger than expected variations in mortality rates for each death and tend to show high mortality rates despite small numbers of overall deaths, in what is commonly termed the "small number problem" (Borden and Cutter 2008; Meza 2003; Lawson 2001). To adjust for this, an empirical Bayes transformation using the Gamma model with method of moments estimation was used (Meza 2003; Marshall 1991). The transformation requires the calculated SMR for each county, along with information on the observed and expected fatalities. The Gamma model is commonly used as it has a direct solution (Meza 2003) and yields similar results as other more computationally intensive methods (Marshall 1991). Overall, the empirical Bayes method produces a non-zero estimate of SMR that is smoothed towards the mean in counties with a small expected fatality count, while producing a value very close to the SMR in counties with a large expected fatality count. Subsequent mentions of the SMR in this manuscript are referring to the empirical Bayes transformed SMR rather than the raw SMR.

In order to compare the "indirect" fatalities from winter precipitation related motor vehicle and aviation crashes to "direct" fatalities from other meteorological causes, fatality counts from 1996–2011 were gathered for a number of weather hazards from *Storm Data*. While using the entire 1975–2011 period would be preferable, the online version of *Storm Data* only contains information on tornadoes, thunderstorm wind, and hail prior to 1996, making collection of data on fatalities from other sources such as winter weather very difficult. As there can be significant variability in the number of fatalities on an annual basis, the average number of fatalities per year due winter precipitation related automobile and aviation crashes and several "direct" meteorological causes during the 1996–2011 period was used for this comparison. Results of this analysis are important in order to understand the relative contribution of direct and indirect fatalities to the overall losses produced by winter weather, and how these losses compare to losses from other meteorological hazards.

2.4 Results and Discussion

a. Characteristics of motor vehicle fatalities

Winter precipitation was a factor in a total of 31,159 fatalities and 27,326 fatal crashes during the 36 year period of record. In terms of precipitation type, 84% of crashes were attributed to snowfall, with the remaining 16% attributed to sleet or freezing rain. This may be due to several factors. Previous studies (Changnon et al. 2006, Changnon 2008, Changnon and Karl 2003) have found that sleet and freezing rain occur less frequently than snowfall. Another possible factor is that the public may perceive sleet and freezing rain as being more hazardous than snowfall and may choose not to drive or may drive much slower than they would drive during snow or when the pavement is dry (Eisenberg and Warner 2005). Future work will address these possibilities and determine how crash rates respond to changing winter precipitation type.

Temporal trends in winter precipitation related motor vehicle fatalities were explored on multiple time scales in order to understand the annual, monthly, and daily trends of mortality and for comparison to other meteorological hazards. The number of fatalities ranged from a low of 535 in 2006 to a high of 1158 in 1996, while the number of crashes ranged from 458 in 2006 to 1011 in 1996 (Fig. 2.1). Fatalities did show a declining trend through the period. However, the percentage of motor vehicle fatalities related to winter precipitation showed little trend, indicating that the reduction in fatalities is related to improvements in vehicle safety and roadway improvements that have led to a decline in all motor vehicle fatalities, including those which are related to winter weather (Table 2.1). Perhaps not surprisingly, 68% of fatalities and 70% of fatal crashes occurred during meteorological winter (December, January, and February). When examined by month, January had the most fatalities and collisions (7805 fatalities and 6912 crashes), while December had the second most fatalities and crashes (7664 fatalities and 6748 crashes). Winter related vehicle crashes and fatalities occurred in every month except July. The earliest fatal crash of the winter season occurred on 26 August 2006 in Larimer County, Colorado, while the latest occurred on 24 June 1976 in King County, WA. Just 0.48% of fatalities and 0.44% of fatal collisions occurred between 1 May and 30 September. These occurred primarily in the mountainous regions of the western U.S. where winter precipitation can persist well into late spring and early summer.

Fatal motor vehicle crashes involving winter precipitation were further examined by hour of occurrence. The percentage of collisions by hour was calculated for both winter and non-winter related fatal crashes, with non-winter fatal crashes defined as any fatal accident in which the weather was not coded as sleet (code 3) or snow (code 4). Because no winter related fatal crashes occurred between 24 June and 26 August of any given year, those dates were also excluded from the counts of non-winter fatal crashes. This was done so that the two datasets would compare the same range of dates, and to remove the effect of increased summer driving, which may skew the distribution of non-winter fatal crashes. From 2002–2011, the highest rates of fatal vehicle crashes occurred in the summer months (NHTSA 2013).

Winter related and non-winter related fatal vehicle crashes have a very different hourly distribution (Fig. 2.2). A much larger percentage of non-winter crashes occur during the evening and overnight hours (1900–0559 local time), while a larger percentage of winter related crashes occur during the morning and daytime hours (0600–1859 local time). Examination of lighting conditions during each crash revealed that only 45% of winter related fatal accidents occur at night, with another 5% during dawn or dusk. This is surprising as daylight hours are shortest in the winter months, so it would seem likely that a higher proportion of fatalities would occur at night. In comparison, 51% of non-winter related fatal crashes occur at night, with an additional 3% occurring during dawn or dusk. Fatal accidents involving rainfall are similar to non-winter related fatal accidents, with 54% occurring at night and 4% occurring during dawn or dusk. This indicates that the hourly distribution of winter precipitation related vehicle fatalities differs from not only fatal crashes as a whole but also crashes involving rainfall. Eisenberg and Warner (2005) found that people aged 30–50 had increased fatality rates due to snowfall related motor vehicle accidents as compared to those under 18 or over 65 years of age, presumably since adults in the 30–50 age group had to travel to work regardless of the weather. This may in part explain the high number of daytime motor vehicle fatalities involving winter precipitation.

The empirical Bayes transformed standardized mortality ratio (SMR) for each county in the U.S. was log-transformed to obtain a normal distribution and used to examine the spatial characteristics of winter precipitation related motor vehicle fatalities (Fig. 2.3). Positive (negative) values indicate areas where the SMR was higher (lower) than the mean and that saw higher (lower) than expected mortality. As would be expected, the majority of high SMR areas are located in the Northeast, the Great Lakes, and western regions of the U.S., regions where snowstorms are most common (Changnon et al. 2006). In particular, the western U.S. saw several areas with SMRs greater than 2.5 standard deviations from the mean. Areas of SMRs below the mean are evident primarily in the Southeast due to a lack of snowfall, however many urban areas across the U.S. (e.g. Chicago, IL; Minneapolis-St. Paul, MN; New York City; Milwaukee, WI) also have lower than expected values of SMR and ultimately saw fewer fatalities than would be expected given the age and population size characteristics of the county. There are several potential explanations for the lower than expected fatalities in urban areas, including reduced travel speed during winter weather due to roadway congestion, road maintenance practices during winter weather, and use of mass transit as an alternative to driving during winter precipitation. Future research will explore these explanations and others to determine why these areas experience lower than expected mortality.

Previous studies have found that vehicle fatalities are often spatially clustered (Eckley and Curtin 2013). A global Moran's I test was used to determine if the empirical Bayes transformed SMR data were significantly clustered. Neighbors were designated based on the spatial extent of the underlying process which produces the fatalities—winter precipitation. Since 84% of winter precipitation related motor vehicle fatalities involved snowfall, the spatial extent was based on the size of a typical snowstorm. Changnon and Changnon (2007) found that snowstorms in the Eastern U.S. are often elliptically shaped with a major axis of 568 km and minor axis of 171 km, and the average of these two distances (370 km) was then used to determine the neighborhood. The likelihood of positive spatial autocorrelation in the SMR dataset was confirmed, with a Moran's I coefficient of 0.06 ($p < 0.001$).

With the tendency for SMR values to cluster established, a local indicator of spatial association (Anselin 1995) was used to identify significant ($p < 0.05$) SMR cluster locations (Fig. 2.4). Clusters of high and low SMR values are found in many of the locations which saw SMR values 1.5 to 2.5 standard deviations above or below from the mean. Clusters of high SMR are most prevalent in the western U.S., the Upper Peninsula of Michigan, and across parts of New York and Pennsylvania, while low SMR clusters are found primarily across the Gulf Coast and across the Ohio Valley. Perhaps more interesting are the clusters of outliers. In the western U.S., several Low-High clusters exist, indicating areas with low SMR surrounded by areas with high SMR. Many of these clusters contain highly populated urban counties such as Salt Lake City, UT, San Francisco and the Central Valley of California, Las Vegas, NV, and the urbanized counties of the Front Range of Colorado. High-Low outliers, indicating areas with high SMR surrounded by areas with low SMR are found throughout the Southeast, and particularly along the spine of the Appalachian Mountains from north Georgia through West Virginia. Examination of both the Low-High and High-Low outliers provide useful case studies to determine why mortality is different than in neighboring clusters. The overall vulnerability of a place is a product of both the vulnerability to the physical hazard and the vulnerability due to societal factors (Cutter 1996). While it is likely that many factors, both physical and societal, are involved in the pattern of mortality found, future work to identify and mitigate these factors may lead to a reduction in winter precipitation related motor vehicle fatalities.

b. Characteristics of aviation fatalities

The same 1975–2011 period had 1,316 fatalities and 559 aviation accidents related to winter precipitation (Fig. 2.5). The number of fatalities ranged from 139 in 1982 to 4 in 2010. Annual fatality counts are highly sensitive to large events. For example, the 1982 crash of Air Florida Flight 90 during takeoff in snow from Washington D.C. was responsible for 56% of the fatalities found in 1982 and 6% of the total fatalities. However, most winter precipitation related crashes involved smaller aircraft, with an average of 2.35 deaths per crash. Unlike motor vehicle fatalities, there is a discernible downward trend in the number of winter precipitation related aviation fatalities. This reduction is likely due in part to improvements in de-icing procedures and materials, along with improvements in cockpit communication and protocol between the aircraft captain and first officer following the Air Florida disaster (Halsey III, 2012).

While nearly 70% of winter precipitation related motor vehicle fatalities occurred during meteorological winter, the distribution of aviation fatalities and accidents is slightly different. Overall, 49% of winter precipitation related aircraft fatalities and 33% of crashes occurred during meteorological winter, but fatal crashes occurred in every month except July and August. The fatal accident occurring latest in the season was on

26 June 1989 in Granite, OR, while the earliest fatal crash in the winter season occurred on 4 September 1992 in Steamboat Springs, CO. Aviation related fatalities and crashes occurred at higher rates than motor vehicle fatalities and crashes during the 1 May to 30 September period; 5.5% of aviation fatalities and 5.3% of aviation crashes occurred during this period, while only 0.48% of motor vehicle fatalities and 0.44% of fatal auto accidents occurred during the period. Of the aircraft crashes occurring between 1 May and 30 September, the vast majority (96%) occurred in the western U.S.

The spatial patterns of winter weather related aviation fatalities are very different than those of motor vehicle fatalities (Fig. 2.6). Aviation fatalities are concentrated in the western U.S., with relatively few fatalities east of the Rocky Mountains, while the number of motor vehicle fatalities was high in the western U.S., in the Northeast, and in the Great Lakes. The large number of aviation related fatalities in the western U.S. is not necessarily surprising. Most areas in the Intermountain West U.S. see at least one snowstorm of 15.2 cm (6 inches) or more per year, with some areas in the highest terrain having 10 or more of these events per year (Changnon et al. 2006). Falling snow can greatly reduce visibility which can lead to a loss of situational awareness by the pilots. More than one-third of the winter related aviation fatalities and accidents involved controlled flight into terrain, most commonly when mountain tops were obscured by precipitation and pilots crashed into the rising terrain. In addition, accumulation of snow on the aircraft control surfaces can alter the aerodynamic properties of the aircraft and potentially lead to an eventual loss of control of the aircraft through some combination of mechanical failure, inappropriate crew response, or aircraft upset (Belcastro and Foster

2010). These factors, coupled with the proximity of the ground in high terrain areas, leave pilots with little room for error when winter precipitation is encountered.

c. Comparison with Storm Data *and other hazards*

Unlike hazards such as tornadoes (Ashley 2007) and other thunderstorm wind (Black and Ashley 2010) where most fatalities are a direct consequence of the environmental hazard, this research has shown that there are large numbers of indirect fatalities which involve winter precipitation. While *Storm Data* is not intended to capture indirect fatalities from motor vehicle and aviation accidents, it is important to compare these datasets to better understand the limitations of using *Storm Data* (or any specific dataset) when examining hazard losses from winter precipitation (Gall et al. 2009).

Overall, 571 direct fatalities attributed to winter precipitation were found via *Storm Data* dataset from 1996–2011, an average of 36 fatalities per year. For comparison, winter precipitation related motor vehicle crashes were responsible for an average of 817 fatalities per year during the period, while aviation accidents resulted in 13 fatalities per year (Fig. 2.7). Winter precipitation related motor vehicle crashes resulted in far more fatalities per year than any other hazard during the 1996–2011 period. Results of this work found 13,073 motor vehicle fatalities and 208 aviation fatalities, while *Storm Data* contained only 571 winter precipitation fatalities from any cause during the period of record. Combined, these datasets represent 13,852 total winter weather fatalities during the period, of which *Storm Data* contributed only 4%. It is not surprising that there is such a large difference in fatalities between *Storm Data* and the sources used for this study, as winter precipitation related motor vehicle and aviation fatalities are considered indirect and should not appear in official *Storm Data* loss tallies

(NOAA 2007). However, *Storm Data* can include information about indirect fatalities within the narrative that provides additional details about the event (NOAA 2007). To determine if *Storm Data* did account for some indirect fatalities in the narrative, winter precipitation related motor vehicle crashes that resulted in five or more fatalities were compared to information about the same event from *Storm Data*. Previous research has found that *Storm Data* tends to undercount fatalities when a weather event only causes a small number of fatalities (Ashley and Gilson 2009), and the threshold of five fatalities represented the deadliest 1% of winter precipitation related collisions, making it more likely that *Storm Data* would have information about the crash.

Only 46 out of 27,326 fatal motor vehicle crashes caused five or more deaths, and only six out of the 46 had any details or information listed in *Storm Data.* In one of the six cases, the motor vehicle crash fatalities were actually incorrectly categorized as direct fatalities and appeared in official tallies. That particular year saw 17 winter precipitation related fatalities including the six that were incorrectly categorized, meaning that fully 35% of the direct winter fatalities were actually indirect. It is reasonable to assume that other years in *Storm Data* have similar issues with the distinction between direct and indirect winter fatalities, adding further uncertainty regarding the reliability of the data. In terms of fatal aviation accidents, there were 35 events that caused five or more fatalities (accounting for 23% of winter precipitation related aviation fatalities), of which *Storm Data* only had information on two. Based on the analysis of these indirect winter precipitation fatalities, it appears that relying on the narratives provided in *Storm Data* would result in a significant undercounting of indirect fatalities. In addition, caution should be used when examining direct fatality counts from winter weather due to issues encountered when making the distinction between direct and indirect fatalities.

It is important to reiterate that *Storm Data* is not intended to be a comprehensive database of all losses but rather of direct losses only; however it is one of the most commonly used data sources used when examining hazard losses. As such, it is important that users of *Storm Data* understand that for hazards such as winter weather, which result in a large number of indirect fatalities, that *Storm Data* is far from comprehensive and may only represent a small percentage of the actual numbers of fatalities caused by the hazard.

2.5 Conclusions

Between 1975 and 2011, winter precipitation was a factor in nearly 28,000 aviation and motor vehicle accidents which resulted in over 32,000 fatalities, an average of nearly 900 fatalities per year. Fatality totals from winter precipitation related vehicle accidents far eclipse fatality totals from other, more prominent weather hazards such as tornadoes, flooding, and hurricanes. Despite this, these fatalities receive far less attention from the meteorological community as they are “indirect” and occur when the weather creates a situation that leads to a death, while fatalities from events such as tornadoes are “direct” and occur when the storm is a direct agent in the death. Indirect fatalities are not included in counts of weather related mortality in *Storm Data*, resulting in an underestimation of the true impacts of weather events such as winter precipitation that can cause a large number of indirect fatalities. While there are many factors that can lead to a fatal winter precipitation related vehicle crash, the meteorological community plays an important role through forecasting winter precipitation and through communication of the risk of winter precipitation to the public. This work is important as it is among the first to explore the temporal trends, spatial distribution, and excess mortality due to winter related vehicle crashes.

The number of motor vehicle fatalities involving winter precipitation showed a decreasing trend during the period; however the annual percentage of motor vehicle fatalities attributable to winter weather has remained nearly constant through the study period. The decrease in motor vehicle fatalities related to winter precipitation is proportional to the overall decrease in all motor vehicle fatalities, and it is likely that the decrease in winter precipitation related deaths is the result of improvements in vehicle and roadway safety that have led to a decline in all motor vehicle fatalities, including those which are related to winter weather. This is consistent with the findings of Andrey (2010), whose analysis of 10 Canadian cities for 1984–2002 found that while the relative risk of crash during rainfall had decreased, the risk of crash during snowfall had not changed over time, and in some cases had increased slightly. Andrey (2010) speculates that the risk from snowfall remained relatively constant due to increased driving speeds in snow as a result of better road engineering or winter maintenance. Another possibility is that reduced winter maintenance due to shrinking budgets may be responsible for the trend (Andrey 2010). Improved vehicle safety equipment such as airbags or anti-lock brakes could also give drivers a false sense of security and lead to riskier driving behavior. Future work will further examine these trends and determine how crash rates may change in response to snow versus other frozen precipitation and if factors such as precipitation intensity and timing affect the rate of fatal crashes.

Most fatal motor vehicle crashes involving winter precipitation occur during the daylight hours, while fatal crashes involving other weather conditions are more prevalent at night. Age-adjusted standardized mortality ratios reveal significant clusters of increased mortality in the western U.S. and areas of New York and Pennsylvania, while several urban and Gulf Coast locations had clusters of lower than expected mortality. More interesting are the High-Low (indicating areas with high SMR surrounded by areas with low SMR) located mostly in the eastern U.S. and Ohio River Valley, and Low-High (indicating areas with low SMR surrounded by areas with high SMR) clusters found in the western United States. Identification of these clusters is an important first step in determining factors that influence crash risk and collision rates during winter weather. Future work to examine both the High-Low and Low-High clusters will attempt to identify the factors that influence mortality and result in different outcomes as compared to neighboring clusters. It is hoped that once identified, these factors can be used to reduce mortality from winter precipitation automobile crashes across the entire U.S.

Aviation fatalities also followed a declining trend, most likely due to improvement in de-icing procedures and cockpit communications after the Air Florida disaster in 1982. The spatial distribution of fatal winter precipitation related aviation crashes was very different than that of vehicle collisions. Fatal aviation crashes were most common in the western U.S., where winter precipitation can obscure mountaintops or rising terrain and where high terrain can make it difficult for pilots to recover from a loss of situational awareness when precipitation is encountered.

While this study found over 13,000 transportation fatalities which involved winter precipitation during the 1996–2011 period, *Storm Data* only contained 571 winter precipitation related fatalities from any cause, as vehicle fatalities are considered to be indirect and therefore not officially counted in *Storm Data*. *Storm Data* is not intended to capture indirect fatalities, but users of *Storm Data* (or any dataset) must understand the limitations of the data. Users of *Storm Data* must understand that omitting indirect fatalities results in a significant underestimation the number of deaths caused by winter weather. Reduction of mortality due to winter precipitation (or any hazard) requires an understanding of all fatalities, both direct and indirect. The authors echo the call of Gall et al. (2009) for an open, comprehensive dataset of hazard losses, which focuses on accurate counts of losses, both direct and indirect, from all hazards.

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Table 2.1. Total motor vehicle fatalities, winter precipitation related motor vehicle fatalities, and percent of total motor vehicle fatalities attributable to winter weather, 1975–2011.

Year	Total Motor Vehicle Fatalities	Winter Precipitation Related Motor Vehicle Fatalities	Percent of Total Motor Vehicle Fatalities Attributed to Winter Weather
1975	44,525	944	2.12%
1976	45,523	814	1.79%
1977	47,878	921	1.92%
1978	50,331	900	1.79%
1979	51,093	879	1.72%
1980	51,091	1053	2.06%
1981	49,301	810	1.64%
1982	43,945	816	1.86%
1983	42,589	897	2.11%
1984	44,257	857	1.94%
1985	43,825	1037	2.37%
1986	46,087	583	1.26%
1987	46,390	864	1.86%
1988	47,087	821	1.74%
1989	45,582	923	2.02%
1990	44,599	721	1.62%
1991	41,508	788	1.90%
1992	39,250	786	2.00%
1993	40,150	885	2.20%
1994	40,716	741	1.82%
1995	41,817	1046	2.50%
1996	42,065	1158	2.75%
1997	42,013	1051	2.50%
1998	41,501	689	1.66%
1999	41,717	667	1.60%
2000	41,945	989	2.36%
2001	42,196	779	1.85%
2002	43,005	825	1.92%
2003	42,884	973	2.27%
2004	42,836	854	1.99%
2005	43,510	850	1.95%
2006	42,708	535	1.25%
2007	41,259	885	2.14%
2008	37,423	904	2.42%
2009	33,883	642	1.89%
2010	32,885	687	2.09%
2011	32,367	585	1.81%

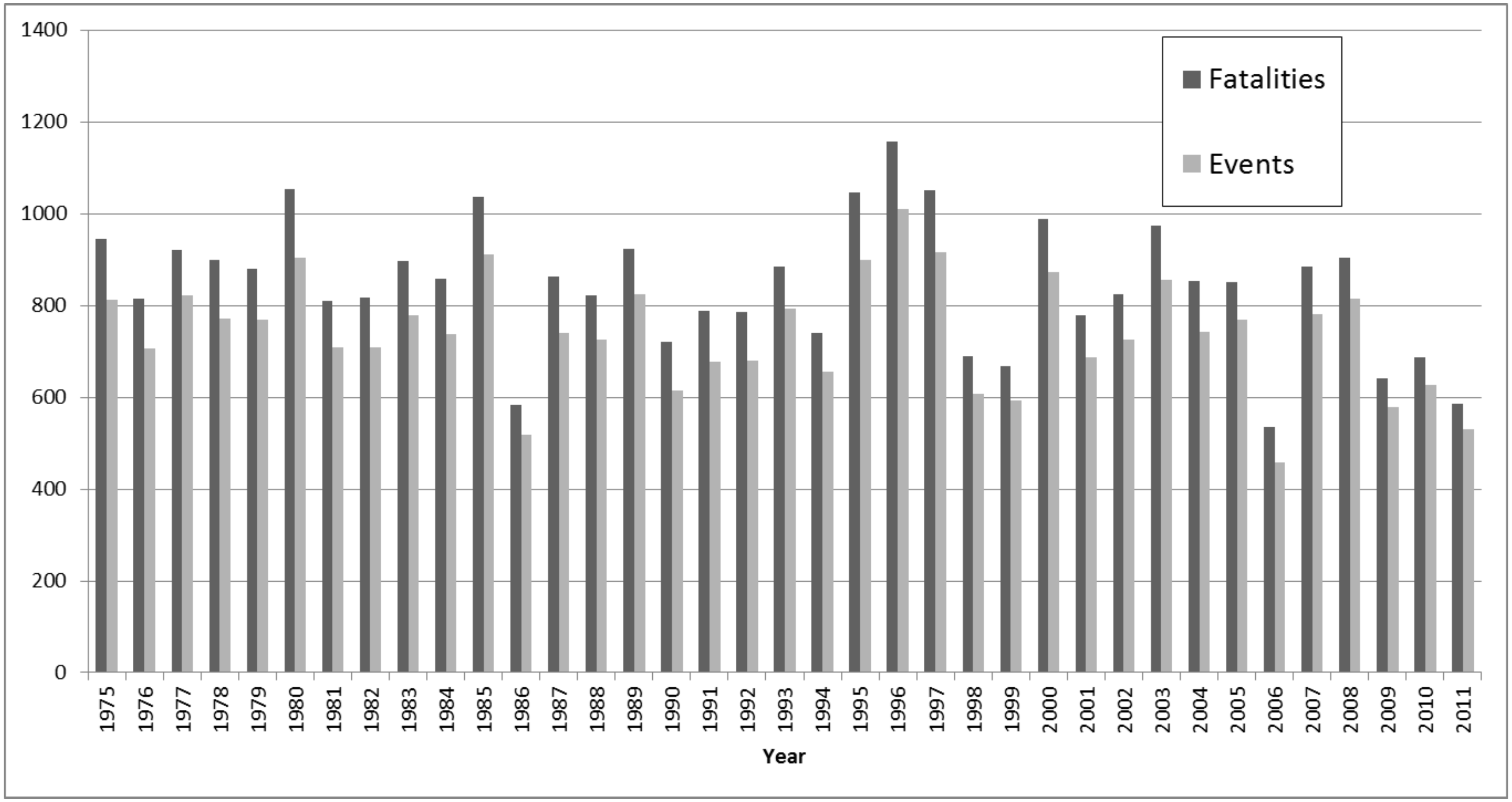

Fig. 2.1 Number of winter precipitation related motor vehicle fatalities (dark gray) and fatal vehicle accidents (light gray) by year, 1975–2011.

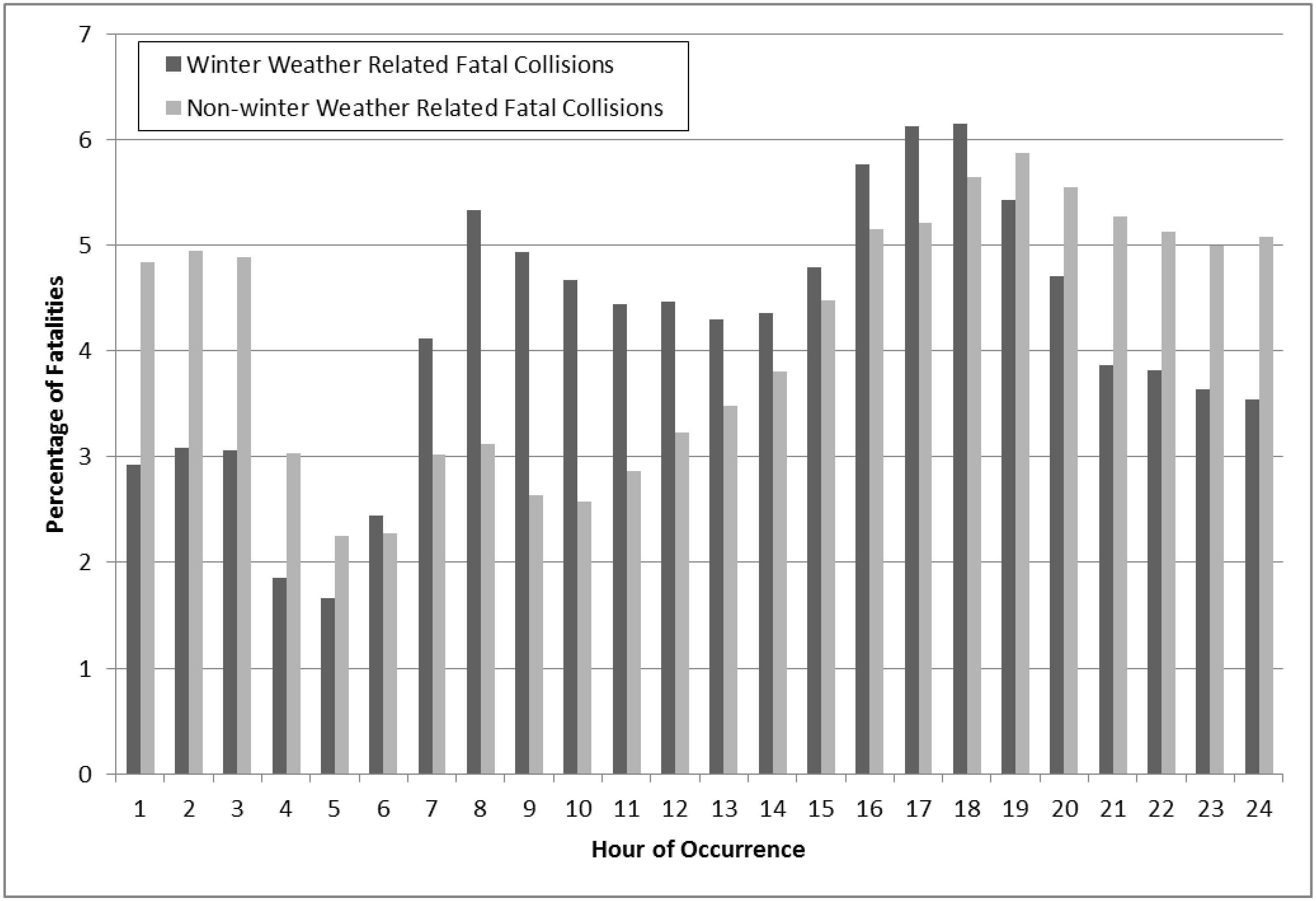

Fig. 2.2 Percentage of winter precipitation related fatal motor vehicle accidents by hour (dark gray) and non-winter related fatal motor vehicle accidents by hour (light gray), 1975–2011.

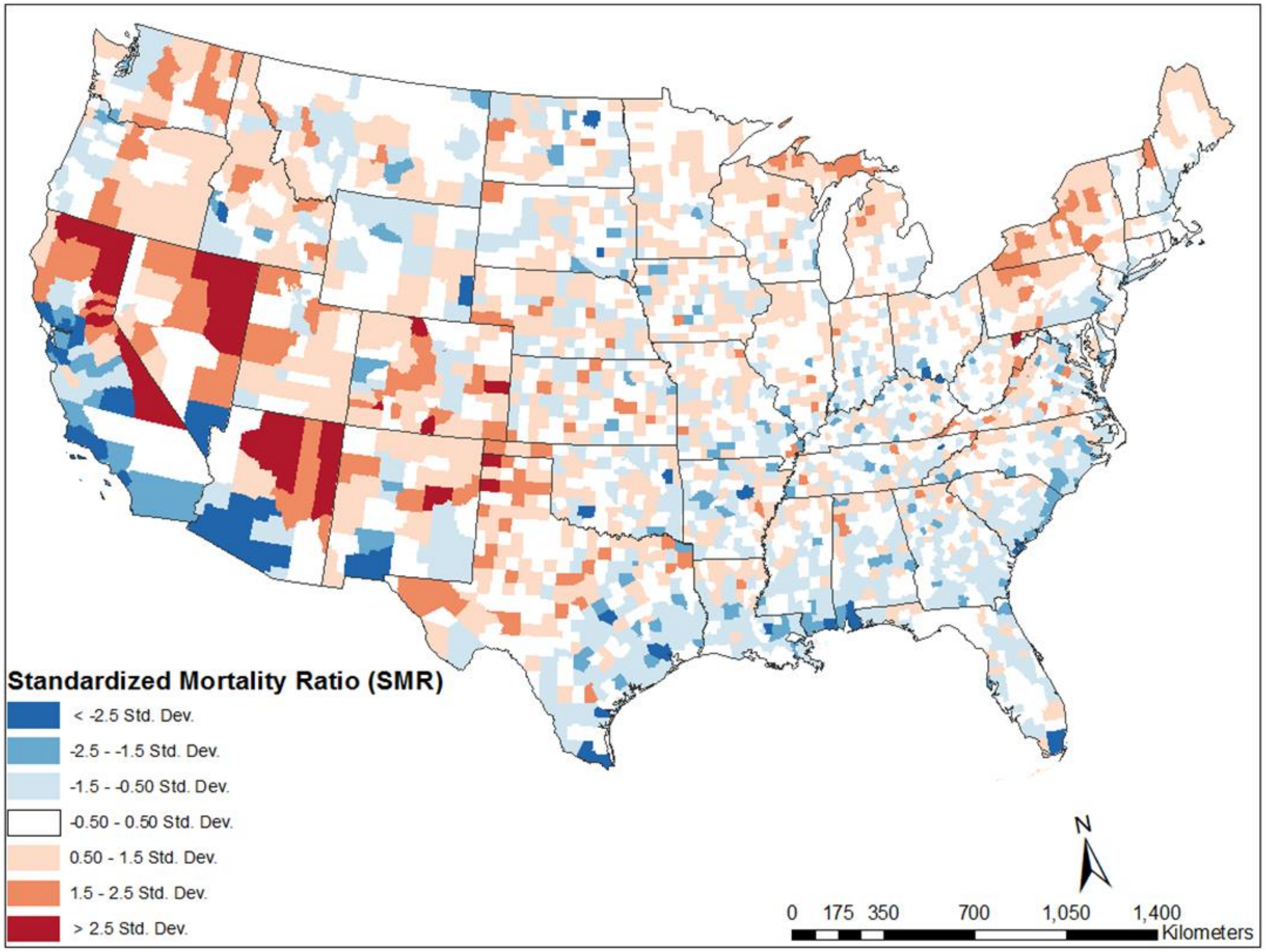

Fig. 2.3 County level Standardized Mortality Ratio (SMR) due to winter precipitation related motor vehicles crashes 1975–2011 after log-transformation to obtain a normal distribution. Positive (negative) values indicate areas where the SMR was higher (lower) than the mean and that saw higher (lower) than expected mortality.

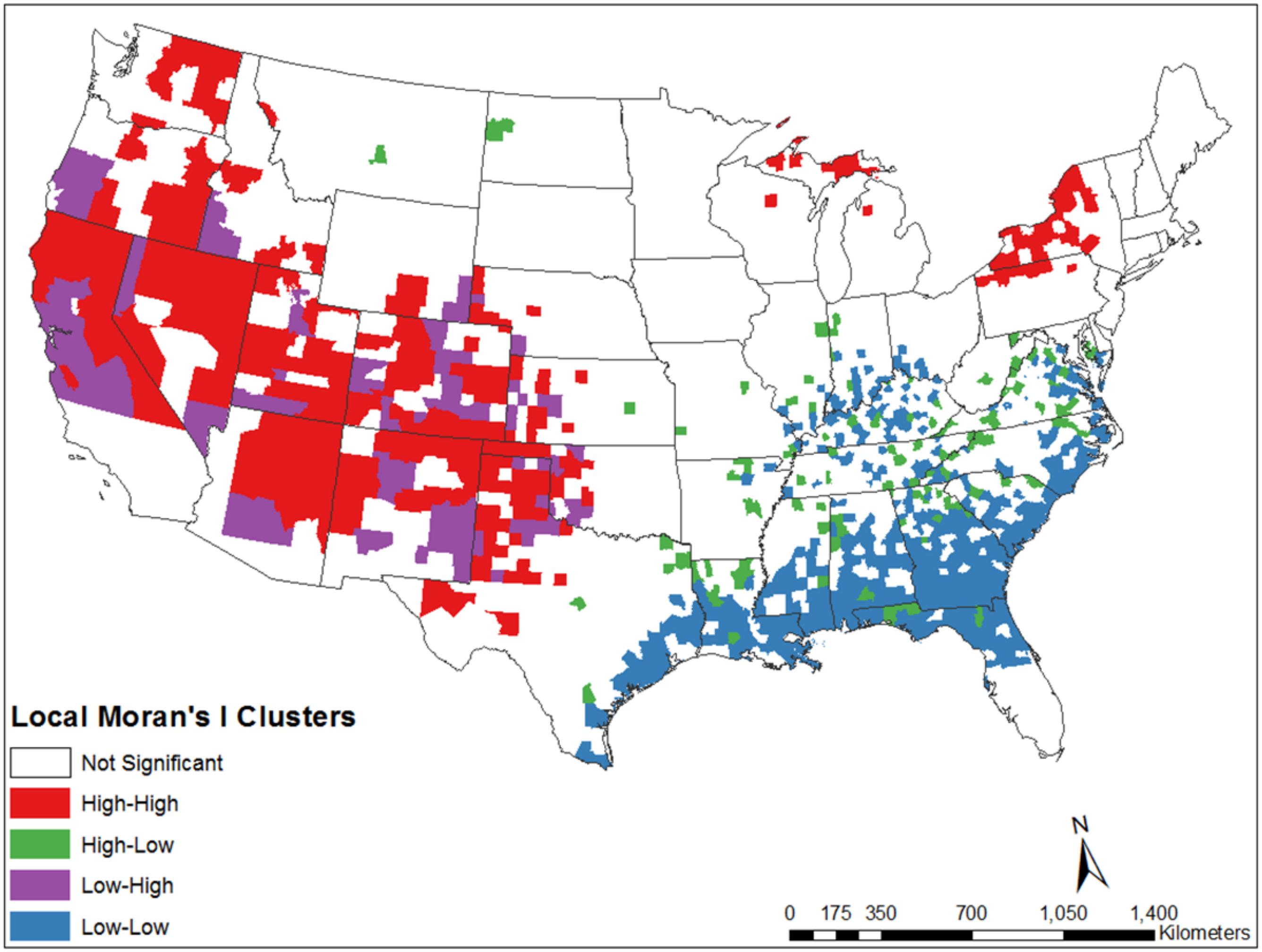

Fig. 2.4 County level Standardized Mortality Ratio (SMR) clusters due to winter precipitation related motor vehicles crashes 1975–2011. All clusters significant at the p=0.05 level.

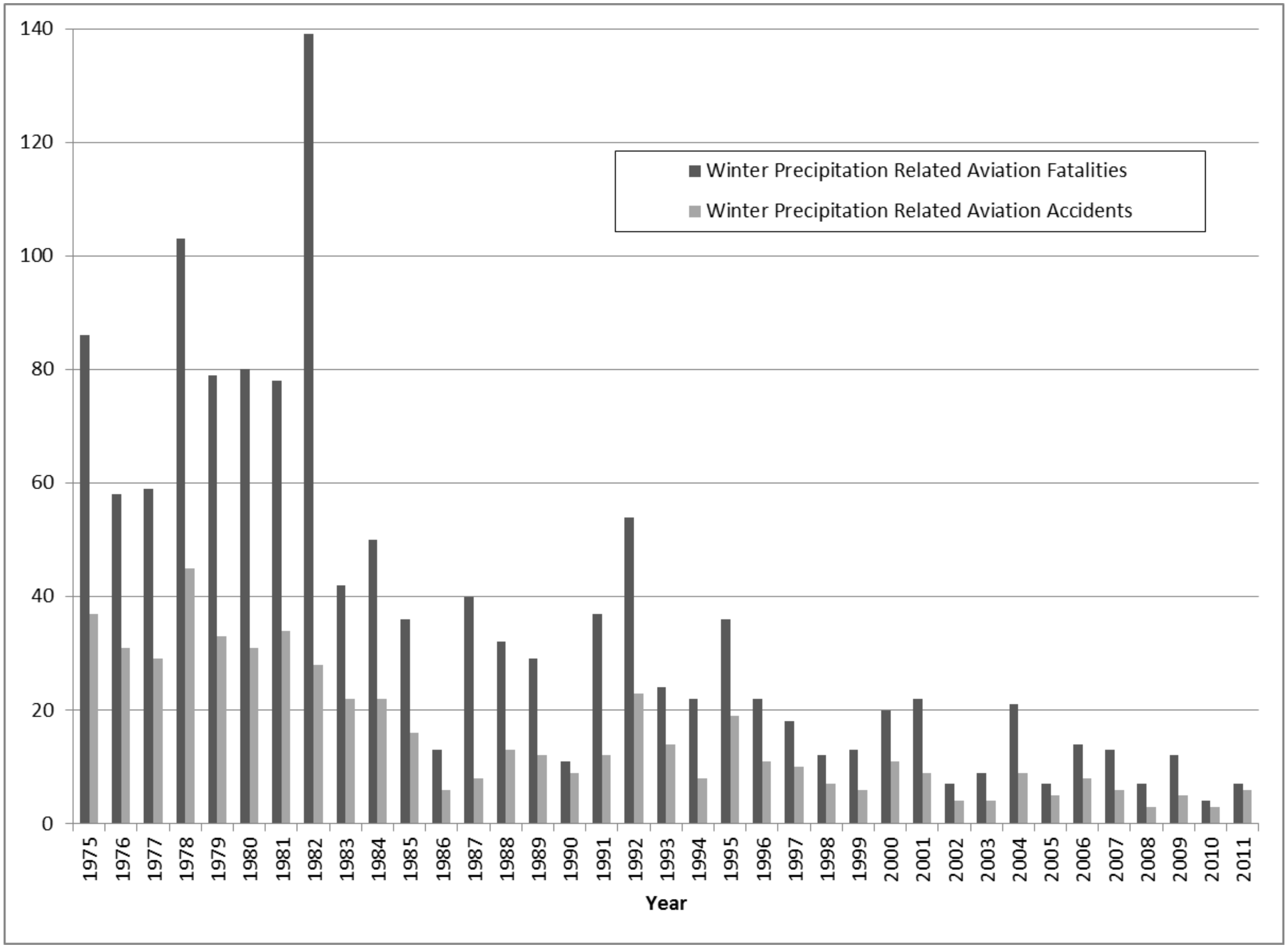

Fig. 2.5 Number of winter precipitation related aircraft fatalities (dark gray) and fatal aviation accidents (light gray) by year, 1975–2011.

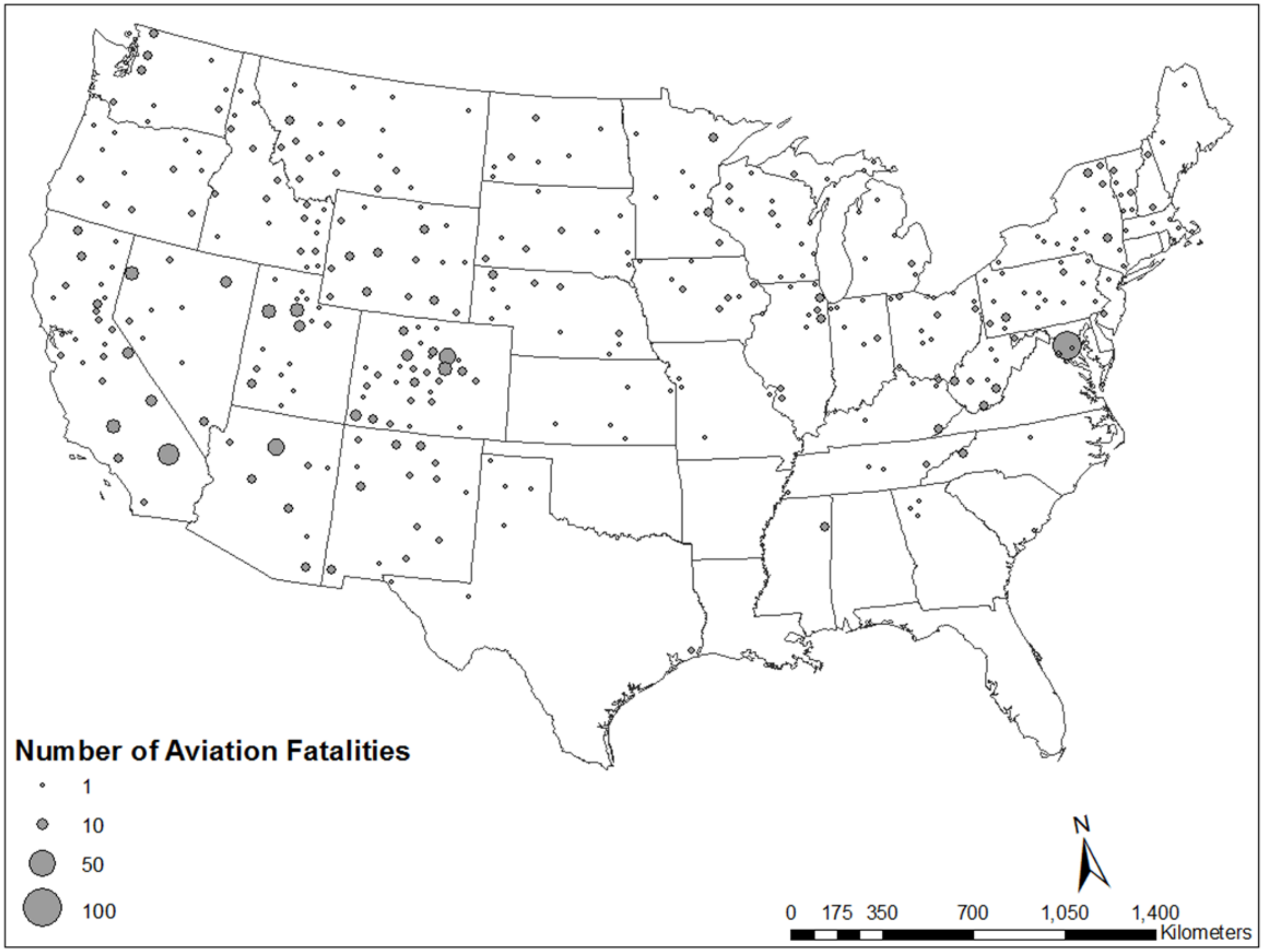

Fig. 2.6 The number of winter precipitation related aviation fatalities by county, 1975–2011.

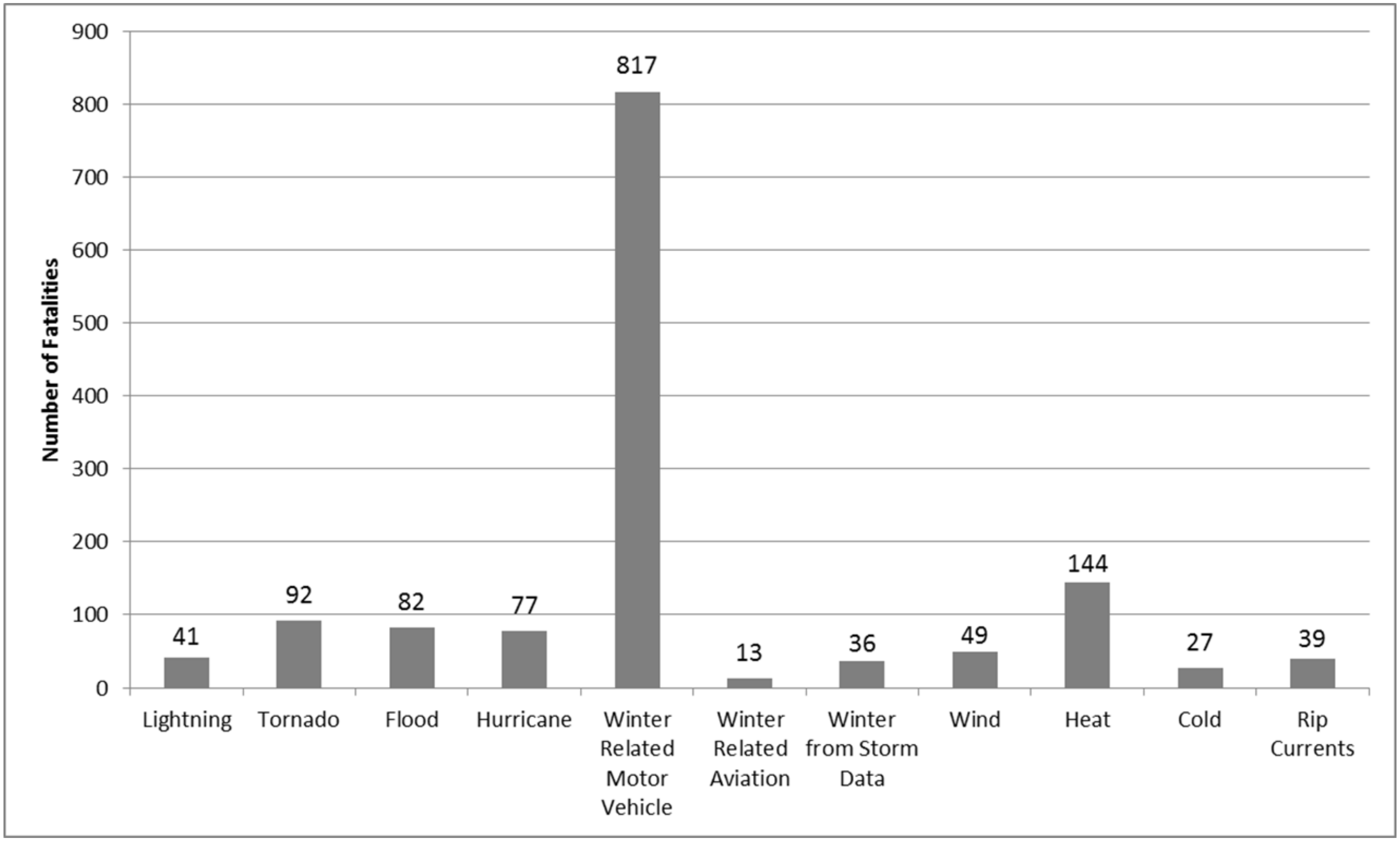

Fig. 2.7 The average number of fatalities per year from various meteorological hazards for the period 1996–2011. Totals for all hazards except winter related motor vehicle and winter related aviation fatalities are from *Storm Data*.

CHAPTER 3

EFFECTS OF WINTER PRECIPITATION ON AUTOMOBILE COLLISIONS, INJURIES, AND FATALITIES IN THE UNITED STATES[1]

[1] Black, A.W. and T.L. Mote. Submitted to *Journal of Transport Geography* on 27 August 2014.

ABSTRACT

To better understand the links between winter precipitation (snow, sleet, and freezing rain) and travel risk, data on weather conditions and vehicle crashes, injuries and fatalities are gathered for 13 U.S. cities. A matched pair analysis is used to construct hourly event-control pairs to determine the relative risk of crash, injury, and fatality. Winter precipitation is associated with a 19% increase in traffic crashes and a 13% increase in injuries compared to dry conditions. The type of winter precipitation (snowfall vs. ice precipitation) had no significant impact on the relative risk of crash. The relative risk of crash was significantly higher during the evening (1800-2359 local time) than during other times of the day. More intense precipitation led to increased relative risk of crash and injury compared to less intense precipitation. Relative risk of crash, injury, or fatality was not significantly higher during the first three winter precipitation events of the year as compared to subsequent events. The relative risk of both winter precipitation crash and injury decreased during the period 1996–2010 period, but crash risk remained elevated as compared to dry days. The sensitivity of U.S. cities to winter precipitation varies from city to city in a manner that is not easily explained. Future research will be required to determine which safety interventions are most effective in each city and revise or expand safety programs appropriately.

3.1 Introduction and Background

In 2010, the World Health Organization declared 2011–2020 the "Decade of Action for Road Safety" in response to the enormous toll that roadway crashes take on individuals, communities, and national economies (WHO 2013). In 2010, 1.24 million people were killed on the world's roads (WHO 2013). In the United States, nearly 33,000 fatalities and 2.2 million injuries occurred due to motor collisions in 2010 (NHTSA 2011). Motor vehicle crashes in the U.S. in 2010 had an economic cost of $277 billion, equal to 1.9% of the U.S. Gross Domestic Product in 2010 (Blincoe et al. 2014).

A number of factors may be involved in a motor vehicle crash. In 2010 in the U.S., alcohol was a factor in 34% of fatal crashes; excessive speed was a factor in 32% of fatal crashes, and distracted driving was responsible for 10% of fatal crashes (Blincoe et al. 2014). These crashes combined accounted for nearly 60% of the economic costs of collisions in the U.S. in 2010 (Blincoe et al. 2014). While use of alcohol, speeding, and distracted driving are within the control of the driver, there are a number of environmental factors that affect the likelihood of driver error and crash, including weather conditions. In the U.S., snowfall leads to an additional 45,000 additional injury-causing crashes and 150,000 property damage crashes per year relative to what would be expected if those days were dry (Eisenberg and Warner 2005).

Since the early 1970s, several studies have examined winter precipitation and its influence on motor vehicle crashes; Table 1 of Andrey et al. (2003) lists a number of studies conducted from the 1970s through the early 2000s. More recent work has examined trends in weather related crash risk, driver adaptation, and collision and injury risk in Canada (Andrey 2010; Andrey et al. 2013; Mills et al. 2011) and the effects of snowfall on collisions, injuries and fatalities in the U.S. (Eisenberg and Warner 2005). These studies consistently demonstrate that risk of both collision and injury are significantly elevated during winter precipitation. Meta-analysis of 34 studies on weather and traffic crashes by Qiu and Nixon (2008) found that snowfall can increase the crash rate by 84% and the rate of injury by 75%, while fatality rates only increased 9% after accounting for reductions in traffic volume. Eisenberg and Warner (2005) found that snowfall days had fewer fatal crashes with the exception of the first snowfall of the year, which had an elevated fatality rate, especially in the elderly. However, an 18% increase in fatality rate was found after adjustment for reduced traffic volume during snowfall days (Eisenberg and Warner 2005).

Available research suggests that driver responses are insufficient to completely offset the risk of driving in weather conditions, which make vehicle handling more difficult, reduce traction, or reduce visibility, which leads to increases in crash rates (Andrey et al. 2013, Eisenberg and Warner 2005). The magnitude of the increase in crash rates depends on factors such as weather conditions (e.g. precipitation type or intensity), time of day, and previous experience with winter precipitation. In a study of 23 Canadian cities, Andrey et al. (2013) found that drivers do not become acclimated to or experience reduced risk of crash during frequently experienced environmental conditions. Further, drivers are less likely to reduce speed in rural areas or areas with higher posted speed limits during both rainfall and snowfall, increasing crash risk as compared to urban areas or areas with lower speed limits (Andrey et al. 2013). Finally, Andrey (2010) found no discernible trend in relative risk (the probability of an event occurring in an exposed group compared to a non-exposed group) of crash due to snowfall in 10 Canadian cities during the period 1984–2002, indicating that casualty rates due to snowfall declined in ways consistent with the overall trend of decreasing vehicle collisions.

These studies leave several unanswered questions. First, what are the spatial patterns of the relative risk of vehicle collision, injury, or fatality during winter precipitation in the U.S.? The Canadian studies (Andrey et al. 2003; Andrey 2010; Andrey et al. 2013; Mills et al. 2011) reveal significant spatial variations in the relative risk of crash and injury across Canada, and previous work in the U.S. by Eisenberg and Warner (2005) examines relative risk in aggregate for the entire U.S. and therefore cannot address this question. Secondly, do factors which were found to affect the relative risk of crash in Canada have a similar affect in the U.S., and do factors such as the type of winter precipitation have an effect? Finally, is the trend in relative risk of crash during winter precipitation in the U.S. similar to the trend (or lack thereof) in Canada?

This study addresses these questions by examining automobile crashes during winter precipitation events and control periods for 13 U.S. cities based on data from 1996-2010 and calculating the relative risk of crash due to winter precipitation. Study cities were chosen to allow analysis of crash risks across different climatic regions of the U.S. and to assess the effects of previous experience with winter precipitation based on the frequency of occurrence in each city. Risk rates were calculated for a number of factors identified in previous research, including precipitation type (snow vs. freezing rain and sleet), precipitation intensity, time of day, and the difference in risk between the first winter precipitation event of the year and subsequent events. Given the number of fatalities, injuries, and property damage that result from vehicle crashes, it is important to examine the characteristics of collisions that involve winter weather in order to determine the vulnerability of U.S. travelers to these events and to mitigate their effects.

3.2. Data and Methods

a. Data sources

Analysis of collision risk due to winter precipitation requires two primary datasets: meteorological data and motor vehicle crash data. Hourly meteorological data from Automated Surface Observing System (ASOS) stations were used as they are available with high temporal resolution (i.e. hourly) and report the type of precipitation (if any) occurring at each observation. Due to their automated nature, ASOS stations are unable to report actual hourly snowfall values and instead report the liquid equivalent amount of precipitation that accumulated in the previous hour. Liquid equivalent measurements are obtained through melting of frozen precipitation that reaches the rain gauge. Converting liquid equivalent measurements back to snowfall amounts is difficult, as the snow ratio can vary from approximately 3:1 (3 inches of snow per inch of liquid) up to 100:1 in some situations (Roebber et al. 2003). ASOS stations may underreport winter precipitation due to changes in airflow near the gauge that can reduce the precipitation reaching the gage or remove precipitation from the gauge before it is melted and measured (Rasmussen et al. 2012). Evaporation as the winter precipitation is melted for measurement and clogging of the recording mechanisms can exacerbate the ASOS underreporting problem (Rasmussen et al. 2012). Despite these issues, ASOS data was used in this analysis due to its high temporal resolution and ability to differentiate between precipitation types. Given the difficulty of the liquid to snow conversion and the desire to compare precipitation totals from three types of winter precipitation (snow, sleet, and freezing rain), liquid equivalent precipitation as reported in the ASOS data was used as the source for precipitation intensity and accumulation for this study.

Motor vehicle crash data was obtained from the National Highway Traffic Safety Administration's (NHTSA) State Data System (SDS). Established in the early 1980's, the SDS consists of computer files coded directly from traffic crash reports that occur in each of 32 states that participate in the system and contains information on fatality, injury, and property damage only crashes. However, the system is far from comprehensive, as some states only provide limited data or for a limited number of years. Further, some states restrict the use of the data by sources outside of NHTSA, reducing the number of states (and the cities within those states) that could potentially be evaluated in this study.

b. Selection of cities

There were several criteria that were evaluated before to selecting cities for this study. The first consideration was the climatology of winter precipitation, to capture both cities where winter precipitation is frequently experienced and those where winter precipitation is relatively infrequent. An additional climatological consideration was type of winter precipitation typically received by each city. Frequency of sleet (Changnon, 2008), freezing rain (Changnon 2003; Changnon and Karl 2003), and snowfall (Changnon and Changnon 2006; Changnon, Changnon and Karl 2006) were considered such that at least one study city would be in a region that frequently receives each type of winter precipitation. Another consideration was to select at least one city that experiences lake-effect snow, as lake-effect snow is typically confined to narrow bands (Niziol 1987) and can result in extreme snow rates (Lavoie 1972), which can lead to rapid changes in driving conditions. Based on these characteristics, 13 locations across the

United States were selected for analysis (Table 3.1). The period of record for each location varies slightly due to crash data availability, but is generally from the mid to late 1990s until the late 2000s, except for California where crash data is only available from 2005-2010.

Once identified, ASOS and SDS data were gathered for each study city. This was complicated by differences in spatial scales between the ASOS and SDS data. ASOS data consists of weather observed at a specific location, typically an airport, while SDS data is aggregated to the county level. In a limited number of states and for a small number of years, SDS does provide details on the location of an automobile accident within a county; however those data provided an insufficient sample size for this study. ASOS data was obtained for the airport closest to (or within) each study city. When two or more airports were present within a city, preference was given to the larger airport or the airport with commercial air service. Both New York, NY, and Chicago, IL have two large, commercial airports (i.e. Kennedy and LaGuardia in New York, and O'Hare and Midway in Chicago). LaGuardia was chosen for New York due to its more central location within the city, while O'Hare was chosen for Chicago as its distance from Lake Michigan makes it less susceptible to lake modification of weather conditions. After selecting the weather station for each city, crash data was obtained for the county containing the weather station. In some cities (Atlanta, GA; Chicago, IL, Cahokia/E. St. Louis, IL, Minneapolis, MN, and Baltimore, MD) crash data was also obtained for other nearby counties, due to the proximity of the weather station to county lines. In the cases of New York, NY, crash data was obtained for the five boroughs which make up New York City.

c. Methods of analysis

A matched pair design is adopted for the study, similar to previous studies of precipitation related crashes in Canada (Andrey et al. 2003; Andrey 2010; Mills et al. 2011). Each hour with winter precipitation is paired with a control hour where inclement weather was absent. Hours with winter precipitation were determined by using the "present weather" field within the ASOS data. If the "present weather" field reported snow, snow grains, ice crystals, ice pellets, or freezing rain, the hour was determined to have winter precipitation. Events where winter precipitation might be mixed with rain (i.e. rain mixed with snow) were eliminated from analysis. Because ASOS can report multiple precipitation types at each observation, if snow was reported with any other winter precipitation type, the event was considered a snow event to maintain consistency with previous studies (e.g. Andrey et al. 2003). Otherwise, the winter precipitation event was categorized as an ice event. In order to control for season, day of the week, and time of day, each winter precipitation hour was matched with a control hour the week prior to or the week after the precipitation event. For example, a three-hour snow event on a Monday morning is matched with a three-hour period one week prior to or one week after the snow event in which no precipitation of any type is recorded. If a winter precipitation event was unable to be matched to a control, the precipitation event was excluded from further analysis. The primary advantage of the matched pair design is that it controls for time dependent variables; however, it does not account for reduction in travel due to inclement weather (Andrey 2010). Hanbali and Kuemmel (1992) showed that estimated that snowfall reduced weekday travel volume anywhere between 7-34%, while weekend travel was reduced between 19-47%, with higher snowfall totals leading to a greater reduction in travel. Knapp et al. (2000) found snowfall led to a 7% to 56% reduction in travel volume, with a mean reduction of 29%. The effects of reduced travel volume will be discussed further in the results of this study, but generally a reduction in travel volume will lead to an increase in risk rates (Eisenberg and Warner 2005; Qiu and Nixon 2008).

Once the crash data was tabulated for event and control periods, estimates of risk of collision were calculated using the odds ratio (Fleiss et al. 2003; Johansson et al. 2009; Mills et al. 2011), following the approach used in studies of crash risk due to precipitation (Andrey et al. 2013; Mills et al. 2011) and darkness (Johansson et al. 2009). Odds are an expression of relative probability, expressed as a ratio of the probability that an event will happen to the probability that the event will not happen (Fleiss et al. 2003). The odds ratio used in this study represents the odds of a crash during winter precipitation (ratio of probability of a crash to the probability of no crash) to the odds of a crash during the control period. Mathematically, this is expressed as

$$OR = \frac{(A/C)}{(B/D)}$$

where A is the number of collisions, injuries or fatalities during the winter precipitation event, B is the number of collision, injuries, or fatalities during the control period, while C and D are estimates of the number of safe outcomes during the winter precipitation event and the control period respectively. The values of A and B are contained in the traffic data, while C and D must be estimated. In their study of Winnipeg, Canada, Mills et al. (2011) notes that there are thousands of vehicle trips or driving maneuvers every hour, resulting in values of C and D that are very large and can be set in a somewhat arbitrary manner. Sensitivity analysis in this study revealed that values of C and D between 10,000 and 10,000,000 resulted in insignificant changes in the odds ratio. A value of 1,000,000 was therefore chosen for C and D to be consistent with Mills et al. (2011). Once calculated for an event-control pair, the odds ratio is then log transformed to obtain a normal distribution. The variance of the logarithm of the odds ratio is:

$$v_i = \frac{1}{A} + \frac{1}{B} + \frac{1}{C} + \frac{1}{D}$$

Each event-control pair is assigned a weight inversely proportional to its variance based on the fixed-effects model for combining estimates of risk (Shadish and Haddock 1994; Johansson et al. 2009; Mills et al. 2011). The statistical weight of each event-control pair is:

$$w_i = \frac{1}{v_i}$$

The weighted mean odds ratio and overall estimate of relative risk of crash based on a set of *g* estimates, where y_i is the log of the odds ratio, is calculated:

$$\overline{y} = \exp\left(\frac{\sum_{i=1}^{g} w_i y_i}{\sum_{i=1}^{g} w_i}\right)$$

Finally, the standard error of the risk estimate was used to calculate 95% confidence intervals for the risk estimate (Johansson et al. 2009; Mills et al. 2011). The relative risk can be used to determine the percent increase (or decrease) in risk as compared to a baseline; for example, a relative risk of 1.40 indicates that collision risk increases by 40% during winter precipitation periods as compared to the control periods. While the relative risk does not determine the absolute risk of a collision, injury, or fatality, it is useful for determining the change in risk due to winter weather and can be used to compare risk between multiple locations.

Results of this analysis initially focus on overall risk levels and variations in risk levels according to injury severity. Subsequent sections address factors identified by previous studies that resulted in increased crash risks: precipitation type (Andrey et al. 2003; Andrey 2010), time of day (Andrey et al. 2003; Andrey et al. 2013), intensity of precipitation (Andrey et al. 2003; Elvik 2006; Brijs et al. 2008; Andrey et al. 2013), and the first snowfall of the year (Andrey et al. 2003; Eisenberg and Warner 2005, Andrey et al. 2013). Finally, the temporal characteristics of winter precipitation related casualty risk are examined.

3.3. Results

a. Combined rates

Overall, 308,619 vehicle crashes, 460 fatalities, and 95,334 injuries were attributed to winter precipitation in the 13 cities examined for this study. The odds ratio for property damage only collision in all cities of 1.19 (95% CI 1.18–1.20) (Table 3.2), indicating that collision risk increases by 19% during winter precipitation periods as compared to the control periods. This is lower than the values of relative risk found by Eisenberg and Warner (2005), for non-first snow days (accounting for 97% of days analyzed in their study) within the U.S. of 1.45. Differences in results between this study and Eisenberg and Warner (2005) likely arise due to the much larger sample size of Eisenberg and Warner (2005) and differences in methods between the two studies. Similar to studies of Canadian cities (Andrey et al. 2003; Andrey 2010, Andrey et al. 2013), there was considerable variation in the relative risk of crash during winter precipitation among the 13 study cities; however each city saw a statistically significant increase of at least 15% over control periods (Fig. 3.1). The smallest increases in relative risk of crash due to winter precipitation occurred at New York, NY, Buffalo, NY, South Lake Tahoe, CA, Mt. Shasta, CA, and Chicago, IL. Each of these cities saw increases that were smaller than the overall 19% increase in risk, and share some characteristics that may partially explain the lesser increase in risk as compared to the other study cities. Both Chicago and New York City have extensive mass transit systems, and residents may decide to travel via mass transit rather than automobiles during winter precipitation leading to a smaller increase in collisions. The relatively small increase in the risk of crash in South Lake Tahoe, Mt. Shasta, and Buffalo may be a direct result of drivers who are well adapted to driving during winter precipitation. Buffalo had an average of over 640 hours per year with winter precipitation during the period of record, the most of any city examined. South Lake Tahoe had 495 hours per year, which was fourth highest, while Mt. Shasta had 322 hours per year. However, Duluth, MN, (560 hours/year), Cleveland, OH (502 hours/year), and Minneapolis, MN (416 hours/year) had similar average annual hours with winter precipitation to Buffalo, South Lake Tahoe, and Mt. Shasta, and crash rates that were higher than the combined rate for all 13 cities.

While 13 cities is not a sufficient sample to determine the spatial pattern of risk across the U.S., there does seem to be a spatial component of the relative risk of crash due to winter precipitation. The lowest values of relative risk are found across the Northeast and Great Lakes, with higher values to the south across the Ohio River and lower Missouri River valley. Cahokia/E. St. Louis, IL and Cincinnati, OH have the largest relative risk due to crash (1.41 and 1.27 respectively) and lie within this zone. Further to the south, relative risk decreases to levels similar to those found in the Great Lakes. It is possible that frequency of winter precipitation is a partial explanation for this pattern. In the Northeast and Great Lakes, winter precipitation is frequently encountered and drivers may be better adapted to driving in these conditions, while in the Deep South, drivers may avoid driving in winter weather conditions altogether due to their inexperience in those conditions. Cincinnati and Cahokia/E. St. Louis may lie in the "sweet spot," where winter precipitation is common enough that drivers are not deterred from driving in it, but where it is uncommon enough that they do not have sufficient experience in adapting to the hazard. It is clear that experience with winter precipitation is not the only factor which influences the relative risk of crash due to winter weather. Other factors, such as the transportation system within each city, snow and ice removal policies, and social vulnerability of the city, among others, contribute to the overall risk of crash (Andrey et al. 2003).

The relative risk of fatality due to automobile crash during winter precipitation for all 13 cities combined is 1.00 (95% CI 0.97–1.04), indicating that the risk of fatal collision is equal between winter precipitation events and control events. This is not necessarily surprising, as Eisenberg and Warner (2005) found that snow days had fewer fatal crashes than dry days (risk ratio of 0.93, 95% CI 0.90–0.97). Previous research has speculated that the near steady fatality rates between events and controls are likely due to drivers reducing speed to adapt to hazardous road conditions, thereby reducing the severity of the crashes that do occur (Andrey 2010; Eisenberg and Warner 2005). Seven of the study cities had fewer than 30 fatalities during either the winter weather or control periods, making it difficult to draw any robust conclusions about the fatal crash rates in those cities. Of the five cities with 30 or more fatalities, two (New York, NY and Minneapolis, MN) had fatal crash rates below 1.0, while three (Cleveland, OH; Buffalo, NY; and Chicago, IL) had fatal crash rates above 1.0; however the difference in fatality rate between events and controls were not statistically significant for any of the 13 cities.

In addition, fatality rates did not show a significant difference between events and controls when disaggregated by precipitation intensity, type, time of day, or first snowfall of the year. Thus, subsequent analysis will focus exclusively on crash and injury rates.

While there was only a modest increase in the relative risk of fatal collision, the relative risk of non-fatal injury due to automobile crash involving winter precipitation for all 13 study cities combined is 1.13 (95% CI 1.12–1.14), indicating that the risk of being injured in an automobile collision increases by 13% during winter precipitation. This is lower than the relative risk of injury of 1.23 for non-first snow days found by Eisenberg and Warner (2005), likely due to differences in sample size and methodology between studies. Similar to overall crash risk, there was considerable variation in the relative risk of injury between the study cities, but each city saw an increase of at least 7% over control periods. This increase was statistically significant in all cities except Little Rock, AR, and Mt. Shasta, CA. Spatially, the relative risk of injury was similar to that of property damage only crashes.

It is important to consider that the relative risk of crash, fatality, and injury presented do not account for reduced travel volume during winter precipitation. Data on traffic volume is not available on the spatial and temporal timescales used in this analysis, so we cannot directly control for reduced exposure to winter precipitation. However, a reduction in traffic volume will result in an increase in relative risk (Eisenberg and Warner 2005; Qiu and Nixon 2008). If we apply the 29% mean reduction in traffic volume found by Knapp et al. (2000) to our sample, we would multiply the results of our analysis by 1.41 [i.e., 1/(1-0.29)=1.41], which represents the increased risk to drivers on the road in winter weather. If we wish to consider the full range of reduced traffic volume estimates (7% to 56%) presented by Knapp et al. (2000), we would multiply the relative risk estimates in this study by 1.08 to 2.27, resulting in relative risk of property damage only crash of 1.29–2.70, relative risk of fatal crash of 1.08–2.27, and relative risk of injury of 1.22–2.56. Overall, this indicates that the relative risk of crash, injury, and fatality may actually be much higher than estimated in this study if winter precipitation leads to a decrease in traffic volume.

b. Precipitation type

Winter precipitation leads to increased relative risk of crash as compared to rainfall (Andrey et al. 2003; Andrey 2010). Differences in precipitation type, especially ice precipitation vs. snow, may be one factor which may lead to an increase in relative risk of crash (Andrey et al. 2003; Andrey 2010). The relative risk of crash during snowfall for all cities combined was 1.17 (95% CI 1.16–1.18), and the relative risk of crash during ice precipitation types was also 1.17 (95% CI 1.14–1.19), indicating no significant difference in relative risk between the two precipitation types. Most cities had crash rates which were higher for ice precipitation than for snowfall (Fig. 3.2); however the difference was not significant in any of the cities. The cities with higher rates for ice precipitation experienced ice precipitation from as few as 4% to nearly 50% of the winter precipitation hours, and so it is not clear that a lack of experience with ice precipitation leads to an increase in the relative risk of crash. In each of the cities with a higher relative risk of crash during snow as compared to ice, snowfall was the dominant winter precipitation type, with over 80% of the winter precipitation hours in each city considered a snowfall event. Given this, a lack of experience with driving in snowfall is not a likely explanation for pattern of relative risk seen in these cities. It is possible that a reduction in travel rates could explain the elevated rates due to snowfall if drivers in these cities significantly reduce their travel during ice precipitation events as compared to snow events. This could occur for a number of reasons, including the perception of ice precipitation as more dangerous to drivers than snowfall. Overall, there is no significant change in relative risk of crash due to winter precipitation as compared to snowfall.

c. Time of day

In their study of 10 Canadian cities, Andrey (2010) found that the relative risk of minimal (minor injuries with no medical attention received at the time of the crash) and minor (injury treated at medical facility but not requiring admittance to the hospital) injury due automobile crash during snowfall was highest at night (defined in their study as the six hour period 0100-0700 Eastern Standard Time), while the relative risk of major and fatal crash was greatest during the afternoon (1300-1900 EST). To examine the effect of time of day on relative risk of crash in the U.S., collisions were divided into four periods based on the time of crash: overnight (0000-0559 local time), morning (0600-1159 LT), afternoon (1200-1759 LT), and evening (1800-2359 LT). Results of this work found that most cities saw significantly higher risk of crash (Table 3.3) and injury during winter precipitation during each of the six-hour time periods. The relative risk of crash for all cities combined was significantly higher during the evening than during any other period. During the evening, the risk of collision increased by 22% (95% CI 20%–23%), and the risk of injury increased 13% (95% CI 11%–15%) as compared to dry periods. Andrey (2010) suggests the combined effects of darkness, driver fatigue, and the inclement weather conditions as potential causes of the elevated risk of crash and injury during the evening and night periods. Of the study cities, seven saw their highest risk of crash and eight saw their highest risk of injury during the evening or night periods. In most cities there was not a significant difference in relative risk of crash or injury among the six-hour periods. Exceptions to this include Atlanta, GA during the overnight period, and Chicago, IL during the evening period. While most cities did have their highest risk of crash or injury during the evening or night periods, several of the study cities did not.

d. Precipitation intensity

Intensity of precipitation (or precipitation rate) has also been shown to increase relative risk of crash during winter precipitation (Andrey et al. 2003; Elvik 2006; Brijs et al. 2008; Andrey et al. 2013). For this analysis, a threshold of 1.02 mm of precipitation per hour (0.04 inches per hour) or greater was chosen to represent heavy winter precipitation as it represented the top 10% of precipitation intensity and resulted in adequate sample size for all study cities. For the 13 study cities combined, precipitation intensity had a significant impact on crash and injury rates. Heavy precipitation resulted in a relative risk of crash of 1.34 (95% CI 1.32–1.36) compared to a relative risk of 1.17 (95% CI 1.16–1.18) during light precipitation. Increased precipitation intensity also resulted in a significantly higher relative risk of injury – 1.19 (95% CI 1.16–1.23) during heavy precipitation as compared to 1.11 (95% CI 1.10–1.12) during light precipitation. All 13 study cities had higher relative risk of crash during heavy precipitation compared to lighter, and four of the 13 study cities saw a significant difference in crash rates between heavy and light precipitation (Fig. 3.3).

Nine of the study cities had higher relative risk of injury during heavy precipitation as compared to light precipitation, and the difference was significant for two cities (Chicago, IL, and Cleveland, OH). In contrast, four cities (Little Rock, AR, Atlanta, GA, Baltimore, MD, and Cahokia/E. St. Louis, IL) had a higher risk of injury during light precipitation as compared to heavier precipitation; however, the difference was not significant for any of the four cities. The difference in cities which have an increase or decrease in the relative risk of injury may be partially explained by differing experience with winter precipitation. The cities with increases in injury risk during heavy precipitation frequently see winter precipitation, while the cities with higher risk of injury during light precipitation have relatively infrequent winter precipitation. In the cities with a greater relative risk during light precipitation, drivers may choose to reduce travel when heavy precipitation is expected due to a lack of experience driving in winter weather. However, drivers in these cities may choose to drive in light precipitation that may not be perceived to be hazardous. In contrast, drivers in the other cities have more experience with winter conditions and may choose to drive regardless of conditions, and may be over-confident in their driving abilities due to their previous experience. While these are just two possible factors which may explain the variation in relative risk of injury, precipitation intensity is clearly shown as a factor that can increase the relative risk of crash.

e. First winter precipitation event of the year

Both Andrey et al. (2003) and Eisenberg and Warner (2005) found that the first three snowfalls of the year led to increased crash risk compared to non-first crashes. Therefore, relative risk of crash and injury for the first three winter precipitation events of the year were compared to subsequent events. Both South Lake Tahoe, CA, and Mt. Shasta, CA, were excluded from this analysis due to the short period of available data, which did not allow for a significant sample. Overall, the relative risk of crash during the first three winter precipitation events of the year was 1.22 (95% CI 1.19–1.25), while the relative risk of crash during subsequent events was 1.19 (95% CI 1.18–1.20). The relative risk of injury was also higher during the first three events of the year, 1.16 (95% CI 1.12–1.20) compared to 1.12 (95% CI 1.11–1.34) for subsequent events; however neither the difference in relative risk of crash or injuries between first events of the year and subsequent events were statistically significant. Most cities had higher relative risk of crash during the first three winter precipitation events of the year, but this difference was significant only in Atlanta, GA. In contrast, Cincinnati, OH had significantly higher relative risk of crash in winter precipitation events beyond the first three of the year. This result indicates that while most drivers are less safe during the first three winter precipitation events of the year, consistent with the findings of Eisenberg and Warner (2005), there are some cities in which drivers are safer during the first three events of the year. One possibility is that drivers are extremely cautious during the first events of the year, but become more accustomed to driving in winter weather and less cautious as the season progresses. It is likely that there are many additional factors that contribute to the differences in rates between first and subsequent snowfalls, an avenue for future research.

f. Temporal trend

Andrey (2010) explored the trends in relative risk of crash for 10 cities in Canada, using data from 1984-2002 and found that the overall risk of casualty in snowfall showed no significant change. The trend in relative risk for both property-damage only and injury crashes was examined to determine if this was also true in the U.S. Unlike the findings of Andrey (2010), there is a significant (p=.006 for crash, p=.004 for injury) downward trend in both the relative risk of crash (Fig. 3.4) and the relative risk of injury

(Fig. 3.5) due to winter precipitation. The primary implication of this finding is that safety of drivers during winter precipitation has greatly improved. For example, in 1996 there were 1157 property damage crashes per 100 million vehicle miles traveled (VMT), and the relative risk of a property damage only winter weather crash was 1.28, indicating that there would be expected to be 1476 crashes involving winter weather per 100 million VMT. In 2010, the absolute crash rate had dropped to 772 property damage crashes per 100 VMT, and the relative risk of crash during winter precipitation had also decreased to 1.14, resulting in an overall expectation of 879 winter precipitation related crashes per 100 million VMT — a decrease of 40%. Similarly, the injury rate in 1996 was 140 per 100 million VMT, with a relative risk of injury during winter precipitation of 1.22, for an overall rate of 171 injuries per 100 million VMT. By 2010, the absolute rate had dropped to 75 injuries per 100 million VMT, with a relative risk of injury during winter precipitation of 1.07, for an overall rate of 80 injuries per 100 million VMT — a decrease of 53%. Despite the drastic decreases in the estimated number of winter weather related crashes and injuries per 100 million VMT, and overall decreases in the relative risk of crash and injury during winter precipitation, the relative risk levels are still elevated as compared to driving during dry weather conditions. Future research will examine the temporal trend of relative risk in additional detail; however this work highlights the need for a continued focus on reducing the relative risk of crash during winter precipitation in order to reduce the hazard that winter weather poses to motorists.

3.4. Conclusions

A number of environmental factors, including winter precipitation, can affect the likelihood of driver error and crash. A matched-pair analysis was used to pair hours with winter precipitation to control hours that were dry in order to compare automobile crashes, injuries, and fatalities between events and controls in 13 U.S. cities. The primary finding is that winter precipitation leads to a 19% increase in crash risk and a 13% increase in injury risk as compared to dry conditions, with no significant difference in the relative risk of fatality. Spatially, the highest relative risk of crash is found across the lower Missouri River and Ohio River valleys; Cahokia/E. St. Louis, IL and Cincinnati, OH have the largest relative risk due to crash (1.41 and 1.27 respectively). The spatial pattern of the relative risk of injury is similar to that of crash, but with elevated relative risk extending in to the southeast U.S.; Cahokia/E. St. Louis (1.25), Cincinnati (1.19), and Atlanta, GA, (1.19) show the highest relative risk of injury due to winter precipitation. While 13 cities is not a sufficient sample to determine the spatial pattern of risk across the entire U.S., these results do suggest there is a spatial component of the relative risk of crash and injury during winter precipitation.

Examining relative risk due to precipitation type, time of day, intensity, and first events showed that no single factor was a consistent predictor of the relative risk of crash or injury. The most reliable predictor was intensity, with 12 out of 13 cities showing an increased relative risk of crash and 9 out of 13 cities showing an increased relative risk of injury during heavier precipitation. Overall, the relative risk of both crash and injury were significantly higher during heavier precipitation. Time of day was the second most reliable predictor, with 11 out of 13 cities experiencing their greatest relative risk during the afternoon (1200-1759 local time) and evening (1800-2359 local time) periods, with the evening period exhibiting significantly higher relative risk of crash than the other six hour periods. In an unexpected finding, no significant difference was found in the relative risk of crash or injury between snowfall events and ice precipitation, although both precipitation types led to an increase in crash risk as compared to dry periods. Finally, the relative risk of crash and injury were higher during the first three winter precipitation events of the year as compared to subsequent events, but the difference was not statistically significant. In contrast with Eisenberg and Warner (2005), no significant difference was found in the relative risk of fatal crash between first precipitation and subsequent precipitation events. Similar to studies of Canadian cities (Andrey et al. 2003) the sensitivity of U.S. cities to winter precipitation varies from city to city in a manner that is not easily explained. Future research will be required to determine which safety interventions are most effective in each city and revise or expand safety programs appropriately. In addition, future research should address aspects of societal vulnerability which would vary on a city by city basis and may contribute to the relative risk of crash.

In contrast with the findings of Andrey (2010) that showed little trend in the relative risk of crash during winter precipitation in Canada, this study found a significant downward trend in the relative risk of both crash and injury during winter precipitation. When combined with the overall downward trend in all types of crashes, this results in a 40% decline in crashes and a 53% decline in injuries per 100 million VMT during winter precipitation. Despite the decline in relative risk during the period, relative risk continues to be elevated during winter precipitation as compared to dry weather.

Consistent with what was found in Canada (Andrey et al. 2013), there is not a clear link between experience with winter weather and reduction in overall relative risk.

It is therefore important to continue research in to the relative risk of crash and injury in the U.S. by exploring additional regions, driver adaptations to winter weather on short time scales (such as reductions in speed), the interactions between weather variables and non-weather elements, and to explore factors such as the importance of weather forecasts and road maintenance to relative risk. It is hoped that these efforts can identify actions that can be applied to reduce the hazard of winter precipitation to motorists.

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Table 3.1 Study Cities

	Period of Record		Counties Used for Crash Data	Airport Used for Weather Data
	Start	End		
Little Rock, AR	1998	2010	Pulaski, AR	Little Rock Adams Field (KLIT)
Mt. Shasta, CA	2005	2010	Siskiyou, CA	Mount Shasta (KMHS)
South Lake Tahoe, CA	2005	2010	El Dorado, CA	Lake Tahoe Airport (KTVL)
Atlanta, GA	1996	2008	Fulton, Clayton, DeKalb, GA	Hartsfield Jackson Intl. (KATL)
Cahokia/E. St. Louis, IL	1997	2010	St. Clair, Madison, IL	St. Louis Downtown (KCPS)
Chicago, IL	1996	2010	Cook, DuPage, IL	Chicago O'Hare Intl. (KORD)
Baltimore, MD	1996	2008	Anne Arundel, Baltimore City, Howard, MD	Baltimore Washington Intl. (KBWI)
Duluth, MN	1996[a]	2010[a]	Saint Louis	Duluth Intl. (KDLH)
Minneapolis/St. Paul, MN	1996[a]	2010[a]	Hennepin, Ramsey	Minneapolis St. Paul Intl. (KMSP)
Buffalo, NY	1996[b]	2009[b]	Erie	Buffalo Niagara Intl. (KBUF)
New York, NY	1996[b]	2009[b]	All 5 Boroughs (New York, Bronx, Kings, Queens, Richmond)	LaGuardia Airport (KLGA)
Cincinnati, OH	1997	2010	Hamilton	Cincinnati Municipal (KLUK)
Cleveland, OH	1996	2010	Cuyahoga	Cleveland Hopkins Intl. (KCLE)

[a] Minnesota crash data unavailable for 2003.

[b] New York crash data unavailable for 2001.

Table 3.2 Relative risk of crash, fatality, and injury due to winter precipitation for all 13 study cities combined.

	Risk estimate (95% confidence interval)		
	Property Damage Only Crashes	Fatal Crashes	Injury Crashes
No Inclement Weather	1.00	1.00	1.00
Winter Precipitation Relative to no Inclement Weather	1.19 (1.18-1.20)	1.00 (0.97-1.04)	1.13 (1.12-1.14)

Table 3.3 Relative risk of crash (and 95% confidence intervals) due to winter precipitation during night (0000-0559), morning (0600-1159), afternoon (1200-1759), and evening (1800-2359) periods.

	Risk estimate (95% confidence interval)			
	0000 to 0559 LT	0600-1159 LT	1200-1759 LT	1800-2359 LT
Little Rock, AR	1.32* (0.99-1.66)	1.14* (0.97-1.31)	1.12* (0.95-1.29)	1.38 (1.16-1.59)
Mt. Shasta, CA	1.13* (0.66-1.61)	1.40 (1.13-1.67)	1.34 (1.07-1.62)	1.24* (0.85-1.63)
South Lake Tahoe, CA	1.10* (0.81-1.40)	1.15* (0.98-1.31)	1.16 (1.03-1.29)	1.09* (0.85-1.26)
Atlanta, GA	1.58 (1.43-1.73)	1.13 (1.02-1.24)	1.01* (0.92-1.11)	1.24 (1.13-1.35)
Cahokia/E. St. Louis, IL	1.23 (1.14-1.32)	1.33 (1.23-1.43)	1.46 (1.33-1.59)	1.29 (1.19-1.40)
Chicago, IL	1.11 (1.09-1.12)	1.16 (1.14-1.17)	1.16 (1.14-1.17)	1.22 (1.20-1.24)
Baltimore, MD	1.20 (1.09-1.30)	1.14 (1.06-1.21)	1.20 (1.13-1.26)	1.19 (1.10-1.27)
Duluth, MN	1.15 (1.04-1.26)	1.18 (1.10-1.25)	1.23 (1.18-1.27)	1.18 (1.09-1.27)
Minneapolis/St. Paul, MN	1.19 (1.14-1.24)	1.18 (1.16-1.21)	1.21 (1.18-1.23)	1.26 (1.22-1.29)
Buffalo, NY	1.07 (1.00-1.14)	1.11 (1.06-1.15)	1.14 (1.10-1.17)	1.12 (1.07-1.17)
New York, NY	1.17 (1.10-1.23)	1.10 (1.06-1.14)	1.12 (1.09-1.16)	1.17 (1.12-1.21)
Cincinnati, OH	1.25 (1.15-1.34)	1.24 (1.19-1.29)	1.21 (1.16-1.26)	1.25 (1.19-1.32)
Cleveland, OH	1.17 (1.12-1.22)	1.16 (1.14-1.19)	1.17 (1.15-1.19)	1.24 (1.20-1.28)
OVERALL	1.13 (1.12-1.15)	1.16 (1.15-1.17)	1.17 (1.16-1.18)	1.22 (1.21-1.23)

* indicates increase was not significant at 95% confidence interval

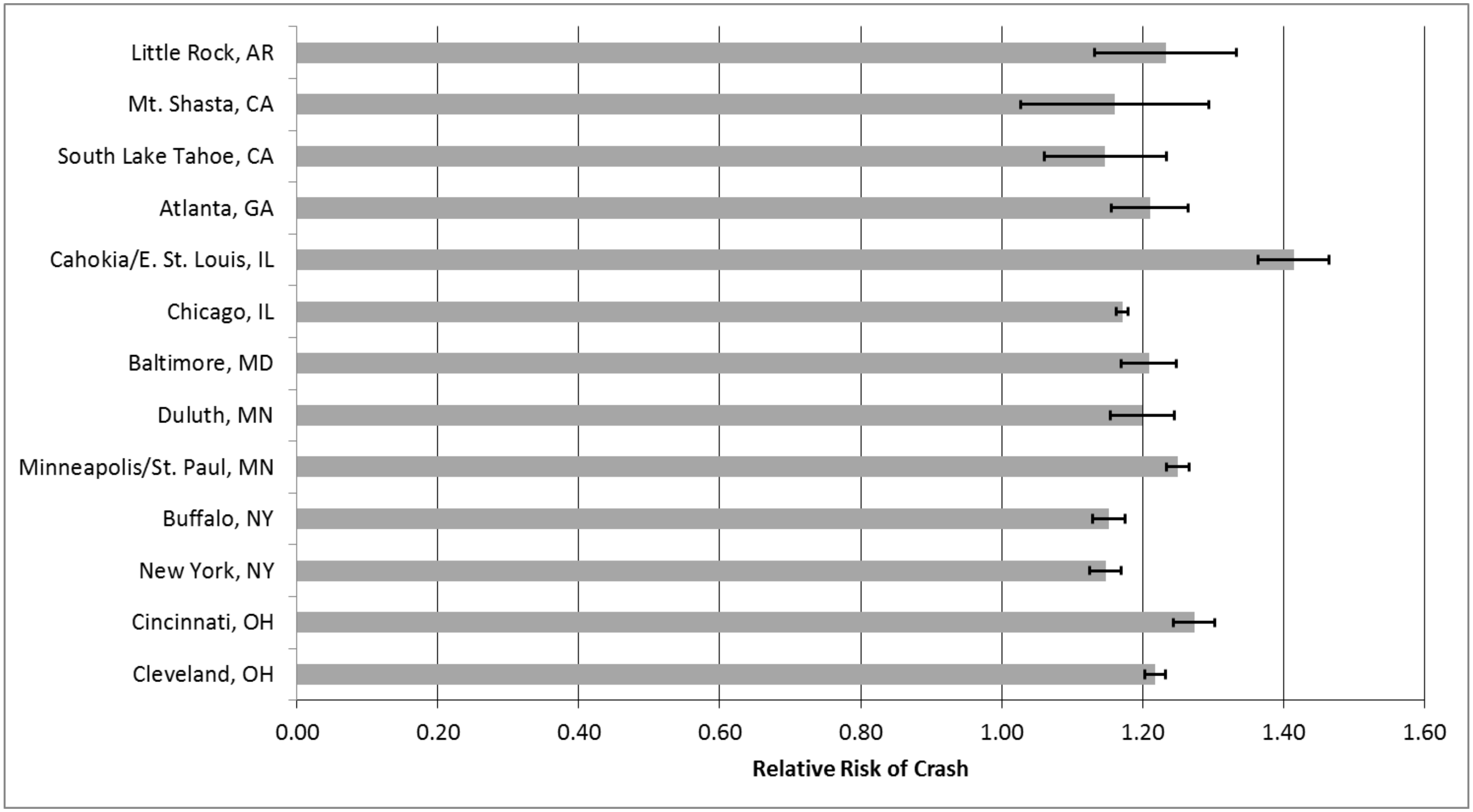

Fig. 3.1 Risk estimates for crash during winter precipitation, with 95% confidence intervals, for 13 study cities.

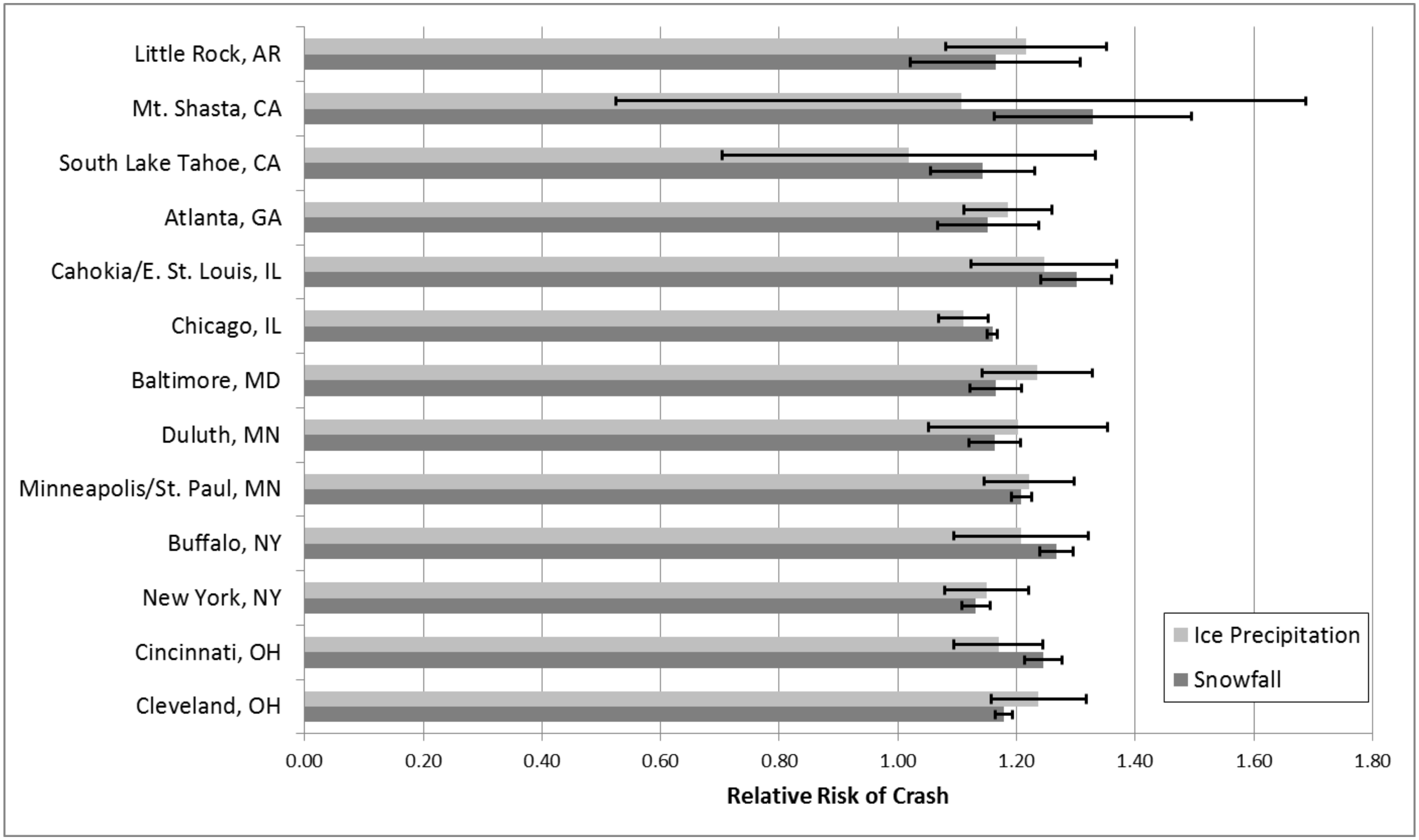

Fig. 3.2 Risk estimates for crash during ice precipitation types (light gray lines) and snowfall (dark gray lines), with 95% confidence intervals, for 13 study cities.

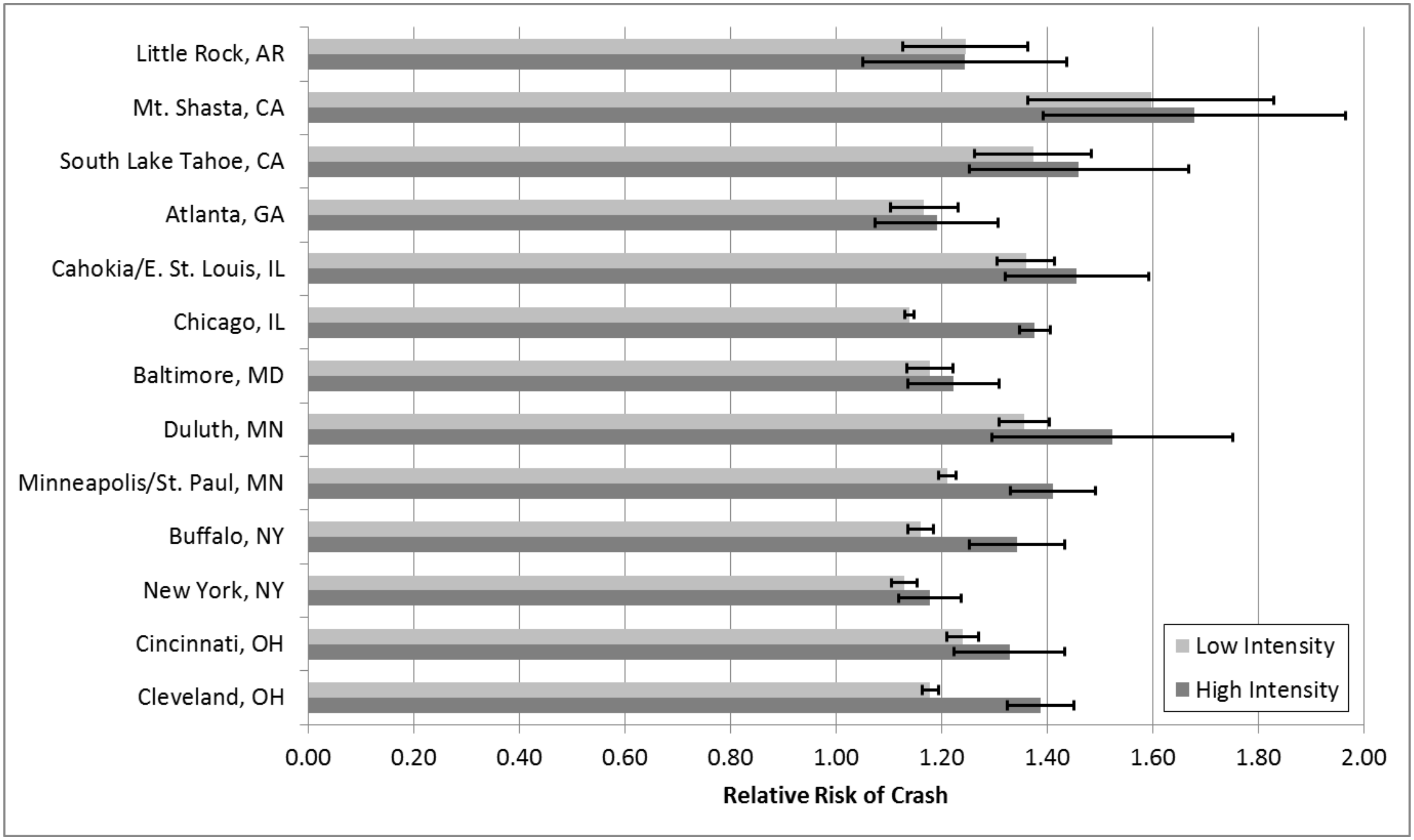

Fig. 3.3 Risk estimates for crash during low intensity precipitation (light gray lines) and high intensity precipitation (dark gray lines), with 95% confidence intervals, for 13 study cities.

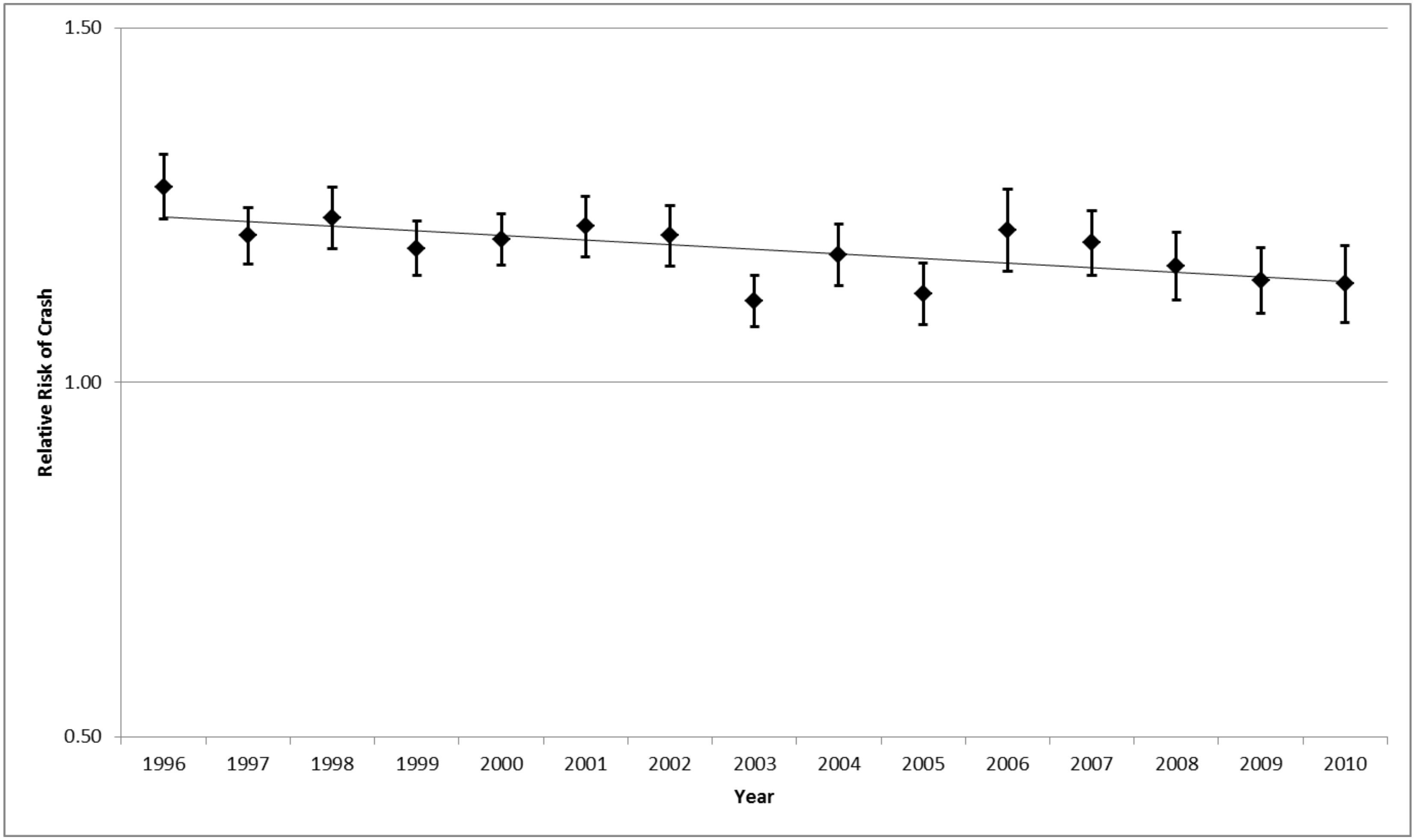

Fig. 3.4 Annual trend in relative risk of crash (and 95% confidence intervals) due to winter precipitation, based on data from all 13 study cities, 1996-2010. Scale from 0.50–1.50.

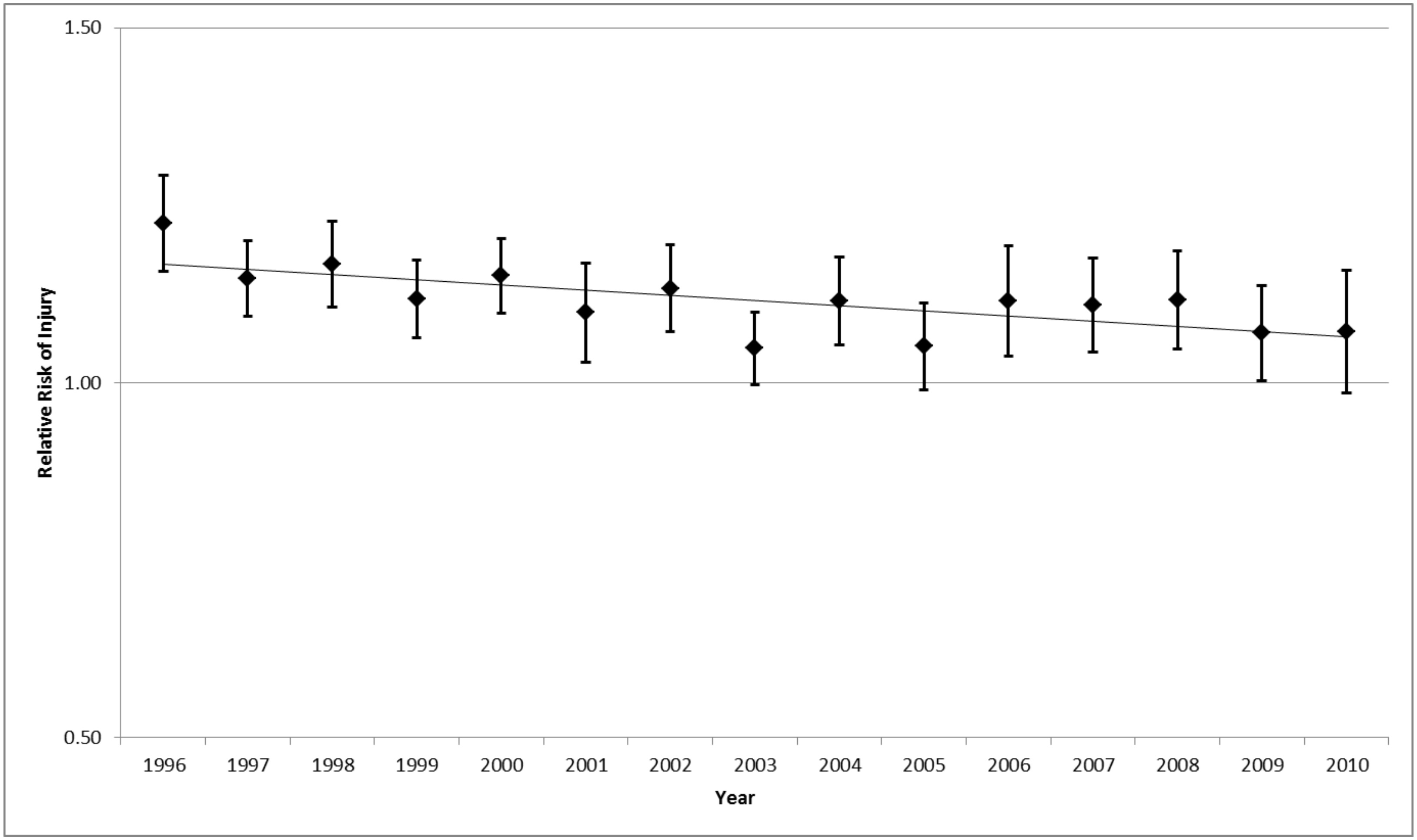

Fig. 3.5 Annual trend in relative risk of injury (and 95% confidence intervals) due to winter precipitation, based on data from all 13 study cities, 1996-2010. Scale from 0.50–1.50.

CHAPTER 4

WINTER PRECIPITATION RELATED CARBON MONOXIDE POISONINGS IN THE UNITED STATES[1]

[1] Black, A.W. and T.L. Mote. To be submitted to *Applied Geography*.

ABSTRACT

Winter weather can cause indirect fatalities—those where the weather leads to circumstances that cause a death. One example of an indirect fatality is carbon monoxide (CO) poisonings that occur when winter precipitation disrupts electrical power. The goals of this study are to examine the demographic and spatial characteristics of these deaths for the period 1984–2004. A comprehensive database of power outage causing winter storms was compiled using data from the North American Electric Reliability Council (NERC) and combined with information on significant snowstorms from the Regional Snowfall Index (RSI). Power outage producing winter precipitation events were then compared to fatal CO poisonings from the National Vital Statistics System (NVSS) to determine which deaths were related to the outages. More than 200 CO poisoning deaths were recorded due to power outages caused by winter weather during the period examined. Most fatalities were among men and those aged 65 or older, similar to other unintentional, non-fire related CO poisonings. Non-Hispanic blacks and non-Hispanic whites are disproportionately affected by winter precipitation power outage related CO poisoning, but Hispanics may be more vulnerable to these events. Most victims had a high school education or less, possibly reflecting other socio-economic factors that may lead to a fatal CO poisoning. Spatial analysis of the deaths found that most were in the mid-Atlantic, while states in the Great Plains and Intermountain West that typically see high rates of CO poisonings had no fatalities. Overall, results of this research are important as they highlight the demographic and spatial patterns of these deaths. It is hoped that this information can improve educational and awareness efforts to reduce deaths in the future.

4.1 Introduction and Background

It is estimated that winter precipitation is responsible for 30–40 (Changnon 2007) or as many as 70 (Borden and Cutter 2008) direct fatalities per year in the United States, while extreme cold is estimated to kill 748 people per year (Dixon et al. 2005). However, these studies only consider direct fatalities, where winter weather is a direct agent in the death (NOAA 2007). Winter weather can also lead to indirect fatalities, where the weather created a situation which led to the death (NOAA 2007). Indirect fatalities from winter weather can arise from a variety of situations, but two of the most common are motor vehicle crashes and carbon monoxide (CO) poisonings (Spencer 2009). Black and Mote (2015) found that winter precipitation related motor vehicle crashes were responsible for an average of 817 fatalities per year from 1996–2011. Outbreaks of carbon monoxide poisoning have occurred following major storms, including winter storms (Hampson and Stock 2006). This study addresses the characteristics of fatal CO poisonings involving power loss during and after winter precipitation. A better understanding of these CO poisonings will result in a more comprehensive picture of the true hazard posed by winter weather.

Winter precipitation and bitter cold can disrupt critical infrastructure such as electrical power. In most cases loss of electrical power will result in no deaths, but outages which are larger in size, longer in duration, or that coincide with other hazardous events can lead to fatalities (Yates 2013). Three death modes or chains of events involving CO poisoning after electricity loss were identified by Yates (2013): loss of electricity supply resulting in generator use, loss of electricity leading to use of an alternative combustion-based heating method, and loss of electricity leading to use of an alternative combustion-based cooking source. In each of the three cases, the initial power loss and subsequent actions lead to an indoor build-up of CO which then leads to CO poisoning (Yates 2013).

Carbon monoxide is a colorless, odorless, and tasteless gas formed due to the incomplete combustion of carbon-based fuels (Johnson-Arbor et al. 2014). Mild exposure to CO can cause flu-like symptoms including fatigue, nausea, vomiting, headache, dizziness, and confusion, while prolonged exposure can cause serious effects such as collapse, coma, cardiorespiratory failure and death (Iqbal et al. 2012b). Many studies have shown that disruptions of electrical power due to winter weather can lead to CO poisoning following sequences of events described by Yates (2013). Iqbal et al. (2012a) reviewed 28 journal articles on CO poisoning from disasters such as hurricanes, winter storms, and flooding and found that most victims were male and over 18 years of age. Generators were the source of CO for over 75% of the fatal incidents, with propane, kerosene, or gas-fueled heaters acting as the CO source in 10% of fatal incidents (Iqbal et al. 2012a). Charcoal grills were the source for the remaining 15% of fatal CO incidents, with these primarily occurring after winter storms (Iqbal et al. 2012a).

Fatal CO poisonings were most common within three days of the disaster onset – 9% of cases occurred on the day of the event, 22% on the day after the event, and 43% on the third day after the event (Iqbal et al. 2012a). Federal mandates require CO warning labels on both generators and charcoal bags (Iqbal et al. 2012a); however many case studies have found that racial and ethnic minorities see a disproportionate number of post-disaster CO fatalities and that in many cases English is not the primary household language, which can lead to confusion or disregard of warning labels (Iqbal et al. 2012a).

Even when CO warning labels are understood and heeded, differences in the perception of what constitutes adequate ventilation for generator use and the amount of ventilation that is actually needed for safe operation can lead to poisonings (Daley et al. 2000).

Case studies that focused exclusively on CO poisonings after winter precipitation such as snowfall or freezing rain found similar results to Iqbal et al. (2012a). Portable generators were the most common CO source, followed by charcoal grills after storms that caused power loss in Connecticut (Johnson-Arbor et al. 2014; Styles et al. 2014) and Maine (Daley et al. 2000). In both studies, most cases of CO poisoning were reported one to four days after the storm, with the second and third day having a large spike in cases as compared to days one and four (Johnson-Arbor et al. 2014; Daley et al. 2000). In at least one study of winter weather related CO poisonings, racial and ethnic minorities and those with English as a second language were the majority of poisoning victims (Styles et al. 2014). Required pictorial labels to warn of CO poisoning on charcoal and generators (Fig. 4.1) were not often seen by victims in Connecticut (Styles et al. 2014) and the labels were only correctly interpreted 74% of the time, falling short of the 85% level recommended by the American National Standards Institute (ANSI) (Styles et al. 2014).

Daley et al. (2000) found that running a generator in a structure attached to the home made it 19 times more likely that someone within the house would be a victim of CO poisoning, while running the generator in the basement made CO poisoning 300 times more likely. Residents chose to operate generators in these locations for several reasons including weather, concerns of theft, and length of extension cords (Styles et al. 2014). Several CO poisoning prevention strategies are suggested by the literature, including educational campaigns (Johnson-Arbor et al. 2014), public service campaigns, including the use of social media, before and after major storms (Johnson-Arbor et al. 2014; Styles et al. 2014; Daley et al. 2000), improved warning labels (Styles et al. 2014), and the use of multi-lingual warnings based on local population (Styles et al. 2014). Nearly all studies of winter weather related CO poisonings are focused on specific cases, potentially limiting the application of their results to a broader population. This study will take a broader approach by examining fatal CO poisonings that result from a winter weather related power outage for the United States for the years 1984–2004 to determine if poisonings across the U.S. share the same characteristics as poisonings identified by previous case studies of disaster related CO poisoning. This study will determine if the findings of the case studies are generalizable to winter precipitation related CO poisonings as a whole. Finally, the study will examine the overall magnitude of fatal CO poisonings and their spatial characteristics. It is hoped that a more complete understanding of winter precipitation related CO poisonings will assist in the continued development of educational and awareness efforts to reduce these fatalities.

4.2 Data and Methods

a. Data sources

Loss of electrical power is the first step in the CO death modes poisoning identified by Yates (2013). Both U.S. Department of Energy (DOE) and North American Electric Reliability Council (NERC) regulations require utilities to report all power disturbances that interrupt service to at least 50,000 customers or interrupt 300 or more megawatts of electrical demand (Hines et al. 2009). Hines et al. (2009) notes that there is significant overlap between the databases. The NERC data is not comprehensive as it only contains information on outages that meet the threshold reporting requirements, and it is estimated that only 4% of outages meet this threshold (Hines et al. 2009). Eto and LaCommarce (2008) echo these findings, noting that most outages are momentary, with durations of five minutes or less, while large interruptions only account for a small portion of the total number of outages experienced by customers. Despite the small number of large power interruptions, large outages account for the majority of the total time without power (Eto and LaCommarce 2008). Longer duration outages also result in an increased need to use alternative methods for heating and cooking, which would result in an increase chance for CO poisoning.

Because the NERC records contain more details, cover a longer period (1984–2006) than the DOE data (Hines et al. 2009), and account for the majority of long duration outages, the NERC database was used as the source of power interruption data for this study. The narrative description of each entry in the NERC records was examined to determine if winter weather was a factor in the outage, and if so, information on the outage was collected for further analysis, including the date, time that the outage began, and location of the outage. Outages that did not involve winter weather or where it was unclear that winter weather was a factor were excluded from the analysis, as were all voltage reductions and voluntary demand reductions, which typically do not result in service disruptions (Hines et al. 2009).

While the NERC database accounts for the majority of long duration outages, preliminary analysis of the data revealed several prominent winter weather events that were not captured by the dataset. Notably, the NERC database did not include information on power outages from the 12–14 March 1993 "Storm of the Century" which caused millions of customers to lose power (NOAA 1994), or the 6–8 January 1996 blizzard that resulted in power outages lasting over two weeks in the Carolinas (Fuhrmann et al. 2009). The Regional Snowfall Index (RSI) (Squires et al. 2014) was used to identify additional snowstorms that may have caused power outages. The RSI is based on the spatial extent of snowfall accumulation, the amount of snowfall, and the population affected by the storm (Squires et al. 2014). The RSI was developed using the snowfall climatology of each of the six easternmost climate regions identified by the National Climatic Data Center (NCDC) (Squires et al. 2014). Each snowstorm from 1900 to 2013 was examined and received a rating from 1 (notable) to 5 (extreme) on the RSI scale (Squires et al. 2014). For this study, the start date, end date, and region affected by any snowstorm receiving a rating of 3 (major), 4 (crippling), or 5 (extreme) between 1984–2004 was extracted for additional analysis. These ratings were selected as major, crippling, or extreme snowstorms are more likely to cause significant disruptions in electrical power that may lead to CO poisonings.

Data on fatal CO poisonings was gathered from the National Vital Statistics System (NVSS) of the National Center for Health Statistics (NCHS), which collects information on births and deaths in the U.S (CDC 2014). Previous studies of CO fatal CO poisonings and CO poisoning surveillance (e.g. Iqbal et al. 2012b) have suggested that the multiple cause-of-death file within the NVSS is the most complete source on of data on fatal CO poisoning because it captures all death events within the U.S. While the multiple cause-of-death data from NVSS is available from 1959 through 2011, the period 2005–2011 has no geographic data, which makes it impossible to compare to the spatial extent of power outages. Therefore, 1984–2004 is used as the period of record for this study to match the availability of power outage data and geographically identified CO poisoning data. Each death within the NVSS is assigned an International Classification of Diseases (ICD) code which describes the cause of death. There is no standard clinical case definition for CO poisoning, and CO poisonings may be listed under several ICD codes. However, the Council of State and Territorial Epidemiologists (CSTE) Carbon Monoxide Surveillance Workgroup (CO-SWG) has developed nationally consistent measures of confirmed, probable, and suspected CO poisoning. The CSTE definition was based on ICD codes (both ninth revision [ICD-9] and 10^{th} revision [ICD-10]) used in death certificates (CSTE 2007).

Similar to Iqbal et al. (2012b), a modified CSTE definition was used to determine CO poisoning mortality cases and their associated ICD-9 (for the years 1984–1998) or ICD-10 (1999–2004) codes. Once identified, these cases were extracted from the multiple cause-of-death file within the NVSS for all deaths occurring in the 48 conterminous U.S. states plus the District of Columbia (Table 4.1). All records of deaths caused by intentional exposure, exposure of undetermined intent, or fire were excluded.

b. Methods

A multi-step process was used to determine if a fatal CO poisoning was related to a winter weather related power loss. The first step was to find additional details about the storms identified using the RSI database. While the RSI database was valuable to determine which storms were most significant, the database only identified the multi-state region affected by the storm; however, finer scale geographic information was needed to determine if the storm resulted in power outages and CO poisoning fatalities. The date of the storm and region affected information from the RSI database was used to identify the storm within *Storm Data*. *Storm Data* is the publication of the National Weather Service (NWS) that records unusual and hazardous weather. Once each RSI event was identified in *Storm Data*, the narrative description of the snowstorm was used to gather additional information about the impact of the storm. If the narrative indicated that the storm caused power outages, the geographic information about the storm was collected, and the storm was retained for further analysis. If the narrative did not indicate that the storm caused power outages or if no information about power outages was reported, the event was excluded from further analysis. The geographic information contained within the narrative was used to determine the spatial extent of the snowstorm. The NERC dataset did not require extensive processing to obtain spatial information as the location of the power outage was contained within the dataset. Each entry in the NERC database also contains the date of the outage and the name of the utility that reported the outage. The service area of the utility was used to identify the spatial extent of the outage. Further, the dataset often included specific information on specific regions or counties affected during each event. Finally, the RSI and NERC datasets were merged based on the date and location of the event, and any duplicates were removed to arrive at the final list of winter weather related power outages.

Each event in the combined winter weather related power outage was then compared to fatal CO poisonings from the NVSS dataset. Case studies of fatal post-disaster CO poisoning found that most were reported one to four days after the storm, with day one defined as the day the storm occurred (Johnson-Arbor et al. 2014; Daley et al. 2000). Additionally, a review of 28 previous studies on fatal disaster related CO poisonings by Iqbal et al. (2012a) found that 88% of fatalities occurred within four days.

To determine if a four day period after disaster onset was appropriate for use in this study, data from the years 1984–1988 was examined to determine the number of fatalities found between one and fourteen days after each winter precipitation event that caused a power outage. Results of this analysis found that 77% of fatalities occurred within four days of the disaster (Fig. 4.2). Further, both this analysis and the analysis of Iqbal et al. (2012a) showed a drastic increase in the percentage of fatalities between days one and three, with a decline after day four. In addition, both studies found that there were no fatalities after the 11^{th} day of the 14-day period. Based on these results and to remain consistent with previous studies, a four-day period was chosen for analysis. Any fatal CO poisonings that occurred in the region that lost power and between one to four days after the outage were considered to be caused by a winter weather related power outage.

Matching based on the date of occurrence was complicated by the availability of temporal data within the NVSS dataset. CO poisoning data from 1984–1988 contained complete information on the date of occurrence and matching was completed simply using the date of occurrence as the beginning of the four-day period. However, data from 1989 to 2004 only includes information on the month and day of week of the death. For the period with limited temporal information, the day of week that the power outage first impacted the region was used as day 1 for matching, and the three subsequent days of the week were also considered to complete the four day analysis period. For example, an outage that began on a Monday was compared to fatalities occurring in the same region during the four-day period Monday–Thursday. Because this method considers the day of the week, it is possible that it could capture some fatalities that are not due to winter weather related outages but instead occurred during the same days of the week but during a different week of the month and are unrelated to the power outage. However, we believe that the potential to capture unrelated fatalities is small. First, only the fatalities occurring within the area of the outage were considered when matching. Within those regions that experienced power outages, it is likely that the majority of the fatalities were related to the outage. Previous research has found that generators and charcoal grills used for home heating were the primary source of CO in 93% of the disaster related CO poisoning fatalities (Iqbal et al. 2012a). As a result, it is very likely that any fatalities that did occur within a region that experienced a winter weather related power outage and during the four-day period of analysis were due to the storm in question and not an unrelated event. Finally, the date, location, and demographic information for each fatal CO poisoning due to a winter precipitation related power outage was extracted from the NVSS.

4.3 Results

There were 226 CO poisoning fatalities attributed to winter weather related power outages in the 1984–2004 period, an average of 10.8 per year. There was considerable variation in the annual number of deaths. The number of fatalities ranged from 57 in 2003, while 1986, 1989, 1990, 1992, and 1995 all had zero deaths. The total of 226 deaths represents just 3.3% of the total unintentional non-fire related fatal CO poisonings reported during 1984–2004. Iqbal et al. (2012a) found that only 0.7% of unintentional, non-fire related CO poisonings during the 1994–2004 period were related to a disaster, and only 46% of those were related to a winter storm. Comparison of the same period based on our data reveals that winter weather related power outages are responsible for nearly 6% of total deaths, nearly 20 times what was found by Iqbal et al. (2012a). Iqbal et al. (2012a) notes that many of the studies of disaster related CO poisoning considered by their meta-analysis examine only small geographic areas, use a limited number of data sources (e.g. a single hospital), or target specific populations, events, or exposures. However, results of this study show that winter precipitation related CO poisonings may account for a much greater share of unintentional, non-fire related CO poisonings than estimated by previous studies, and future efforts to reduce these fatalities may lead to a reduction in overall CO poisonings.

The results of this study reinforce many of the findings of previous research on fatal CO poisonings (Table 4.2). Over 70% of winter weather related power outage CO poisoning victims were men, similar to results found by Iqbal et al. (2012a). This is presumably because men engage in more high–risk activities such as the use of more fuel burning tools or appliances during disasters, such as generators (Iqbal et al. 2012a; CDC 2007). Over 25% of fatalities occurred among those aged 65 or older, which is consistent with all unintentional non–fire CO poisonings (CDC 2007). Symptoms of CO poisoning are very similar to those of other conditions common in this age group and may be dismissed by victims (CDC 2007).

Nearly 71% of winter weather related power outage CO poisonings were among non-Hispanic whites, with non-Hispanic blacks accounting for 17%, other non-Hispanics making up 4%, and Hispanics of any race constituting 9% of victims (Table 4.2). The ethnic breakdown of victims is very similar to that of unintentional non-fire related CO poisonings overall (CDC 2007); however winter weather related power outage poisonings do appear to produce a lesser percentage of non-Hispanic white and Hispanic victims and a greater percentage of deaths among non-Hispanic blacks. It appears that non-Hispanic blacks and non-Hispanic whites are disproportionately affected by winter precipitation power outage related CO poisoning. Based on data from the 2000 U.S. Census, which occurred near the end of the study period, non-Hispanic blacks made up 17% of victims and only 12% of the total U.S. population (Humes et al. 2011), while non-Hispanic whites comprised 71% of victims and 69% of the U.S. population (Humes et al. 2011). In contrast, Hispanics make up 13% of the U.S. population according to the 2000 census, and only accounted for 9% of victims of winter precipitation power outage related CO poisoning. Significant differences were found in the ethnicity of victims of CO poisoning in this study as compared to previous disaster related CO poisoning research. Iqbal et al. (2012a) found a much lower percentage of non-Hispanic whites and higher percentages of Hispanic and other non-Hispanic victims. Differences in ethnicity between winter weather related poisonings in this research and the results of Iqbal et al. (2012a) may be due to the focus on specific populations in the studies analyzed by Iqbal et al. (2012a). Further, Iqbal et al. (2012a) examined deaths from CO poisonings caused by tropical cyclones, winter weather, and flooding. Each of these events has a different climatology and impacts, and each may affect diverse ethnicities in a very dissimilar manner.

The percentage of Hispanic victims of fatal CO poisonings due to winter precipitation related power outage is significantly lower than what was found in the analysis of post-disaster CO poisoning by Iqbal et al. (2012a). Hispanics accounted for nearly 20% of fatal cases in Iqbal et al. (2012a), as compared to 9% of cases in this study. It is possible that the differences between these studies are due to difference in exposure to both winter weather and tropical cyclones between Hispanic and non-Hispanic populations. Hispanic populations are heavily concentrated in the south and southwestern U.S., areas where winter precipitation is infrequent (Fig. 4.3). In addition, the southern U.S., especially parts of Florida and Texas, are affected by tropical cyclones, and fatalities from these storms were included in the results of Iqbal et al. (2012a).

Despite the relatively low number of fatalities found, Hispanic populations may be more vulnerable to fatal CO poisoning when winter weather causes power outages. Some Hispanics may have difficulty communicating in English and may not understand warnings that are disseminated by traditional news sources or warning labels placed on charcoal and generators to warn of CO poisoning (Houck and Hampson 1997). Further, it is suggested that Hispanics may be more inclined to use charcoal indoors as solid fuel has traditionally been used for indoor cooking or heating purposes (Iqbal et al. 2012a; Houck and Hampson 1997). These societal factors and others may make Hispanics more vulnerable to CO poisoning when power outages occur due to winter weather. This vulnerability may be compounded in locations where winter precipitation is less common or where there is significant migration, as both of these would result in less experience with and awareness of winter weather hazards such as winter precipitation power outage related CO poisoning. For example, nearly 30% of fatal winter precipitation power outage related CO poisonings among Hispanics across the U.S. occurred in North Carolina. Winter precipitation is relatively infrequent in North Carolina, which has the 15th largest Hispanic population of any U.S. state in 2000 (Humes et al. 2011) and saw its Hispanic population grow by nearly 400% between 1990–2000. While Hispanics only account for 4.7% of the population of North Carolina in the 2000 census, 29% of fatal winter precipitation power outage related CO poisonings victims within North Carolina were Hispanic. However, the CDC is now working on a comprehensive CO prevention strategy involving 17 languages and has developed other materials designed for diverse audiences (Iqbal et al. 2012a). Ideally, this program will be effective in communicating the risk of CO poisoning to Hispanics and other at-risk minority populations.

Approximately 66% of the poisonings had information on the place where the death occurred (Table 4.2). Of those, 81% occurred in a residential setting. Previous research has found that over 93% of disaster related CO poisoning fatalities were related to improper generator use or operation of charcoal or gas grills indoors (Iqbal et al. 2012a). Further, only 36% of homes have a working CO alarm, which would alert residents to dangerous buildup of CO (Iqbal et al. 2012b). Lower prevalence of working alarms is reported among those living in manufactured housing, renters, and those living below the poverty level (Iqbal et al. 2012b). It is unknown what percentage of homes have an alarm with a battery backup, which would be required in order to alert residents when electrical power is disrupted during a winter weather event. Iqbal et al. (2012b) notes that efforts to increase adaptation of battery powered or battery backup CO alarms would be a valuable public health intervention as it could prevent a large number of CO poisonings, and this research supports that conclusion.

Incidence of CO poisoning appears to be highest among those with high school education or less (Table 4.2). Low levels of educational attainment may increase the likelihood that a victim will have trouble reading and understanding warning labels on generators and charcoal. Further, there is a link between lower educational attainment and other factors such as living below the poverty level and renting, which make it less likely that victim has an operating CO alarm (Iqbal et al. 2012b). Nearly 80% of fatal CO poisonings related to winter weather power outage occurred in those who have a high school education or less, while this group only accounts for 48% of the overall U.S. population. Nearly 30% of deaths were attributed to those who did not complete high school. Of this group, 14% of the victims were non-Hispanic blacks, 7% were other non-Hispanic, and 53% were non-Hispanic whites. Hispanics made up 25% of the fatalities among those with less than a high school education; however, 83% of the total number of Hispanic victims had less than a high school education.

Spatially, fatal CO poisonings related to winter weather power outages are most common across the Mid-Atlantic states (Fig. 4.4). In contrast, very few deaths are seen across the Great Plains and Intermountain West. It should be noted that trees cause more than half of the damage to electrical distribution networks (Ward 2013), and lack of tree cover may partially explain the absence of fatalities evident in the Great Plains. However, the highest rates of fatal unintentional non-fire CO poisoning are typically among Western and Great Plains states such as Wyoming, Montana, Nebraska, and North Dakota (CDC 2007), none of which see any deaths due CO poisoning caused by winter precipitation related power outages. Another possible explanation for few identified fatalities in the Western and Great Plains states is that these regions do not experience power outages large enough to be considered by the NERC data due to low population density and few large cities. If there are power outages but they do not meet the reporting threshold, they would not make it in to the NERC dataset for this analysis even though they could be producing CO poisoning deaths. Future work will explore this in more detail. While only around 20% of the U.S. population lives in rural areas, 29% of fatal power loss CO poisonings victims reside in rural areas. Presumably, these areas may be isolated and without power for longer duration during outages, increasing the likelihood for use of CO producing appliances. Future work will also address this question.

4.4 Conclusions

Typically, loss of electrical power will result in no deaths, but outages which are larger in size, longer in duration, or that coincide with other hazardous events can lead to fatalities (Yates 2013). This study considers fatal CO poisonings due to power loss caused by winter precipitation by combining data on electrical loss, major snowstorms, and deaths due to unintentional non-fire related CO exposure. Many previous studies have examined CO poisonings related to specific winter precipitation events; however, this study is the first to examine deaths related to winter weather across the entire U.S.

Overall, there were 226 deaths due to winter weather power outage related CO poisonings during the 1984–2004 period, an average of 10.8 per year. While this number only reflects 3.3% of the overall number of fatal unintentional non-fire related CO poisonings during the period, it is possible that our methods underestimate deaths as we only considered large power outages and the more significant snowstorms based on the RSI, while smaller outages and storms were not considered. Comparison of the period 1994–2004 to previous studies reveals that winter weather related power outages are responsible for nearly 6% of unintentional non-fire related CO poisoning deaths, nearly 20 times what was found by Iqbal et al. (2012a). These results show that winter precipitation related power outages are a risk to public health, and that the risk may be greater than previously estimated.

Many of the results of this study are consistent with previous case studies of winter precipitation related CO poisoning, indicating that those findings are generalizable beyond specific cases. Deaths were most common among men and those aged 65 or older, similar to other studies of disaster related CO poisoning and unintentional non-fire related CO poisonings overall (Iqbal et al. 2012a; CDC 2007). However, significant differences were found in terms of ethnicity between this and previous studies of disaster related poisonings. These previous studies (Iqbal et al. 2012a) found a much lower percentage of non-Hispanic whites and higher percentages of Hispanic and other non-Hispanic victims. It is possible that the differences are due to difference in exposure to winter weather between Hispanic and non-Hispanic populations. However, it does appear that Hispanic populations may be more vulnerable to CO poisonings that are a result of winter precipitation related power outages when they do occur. However, based on this research, it appears that non-Hispanic blacks and non-Hispanic whites are disproportionately affected by winter precipitation power outage related CO poisoning. Therefore, interventions that can reach both Hispanic and non-Hispanic audiences are needed, although areas with large Hispanic populations should be aware of the vulnerable nature of that population.

Examination of the educational attainment of victims revealed that nearly 80% of victims had a high school education or less. Hispanics in particular had a large percentage of victims with less than a high school education, which may imply that the victims had difficulty in reading and understanding warning labels placed on generators or other CO sources (Houck and Hampson 1997). Further, they may have difficulty communicating in English, making it less likely that they will receive health information on CO poisoning before a disaster (Houck and Hampson 1997). It is very important therefore to continue the efforts at multi-lingual outreach and education discussed by Iqbal et al. (2012a) in order to reach Hispanic and other vulnerable minority populations.

Another important contribution of this study is the examination of the spatial patterns of fatal CO poisonings related to power outages caused by winter weather. A unique distribution is found, with most fatalities in the mid-Atlantic, and few fatalities found in the states that typically see the highest death rates from CO poisonings. Further, around 20% of the U.S. population lives in rural areas, but 29% of deaths occur in rural areas.

It is clear from this research that power loss due to winter precipitation can lead to CO poisonings. As Iqbal et al. (2012a) notes, these events and the high risk behaviors that lead to CO poisoning follow a relatively predictable timeline. A multi-lingual public information campaign launched when a winter storm that is expected to produce widespread power outages is forecast could preempt many of these risky behaviors and lead to a decline in these fatalities. Further, there is typically a lag of one to four days between winter weather occurrence CO poisonings, providing additional time to alert the public to avoid risky behavior. Overall, we echo the conclusions of Iqbal et al. (2012a; 2012b) for a continued effort in communicating CO poisoning related health information to the public, for increased surveillance of CO poisoning cases, and a reduced reliance on secondary data sources to assess CO exposure.

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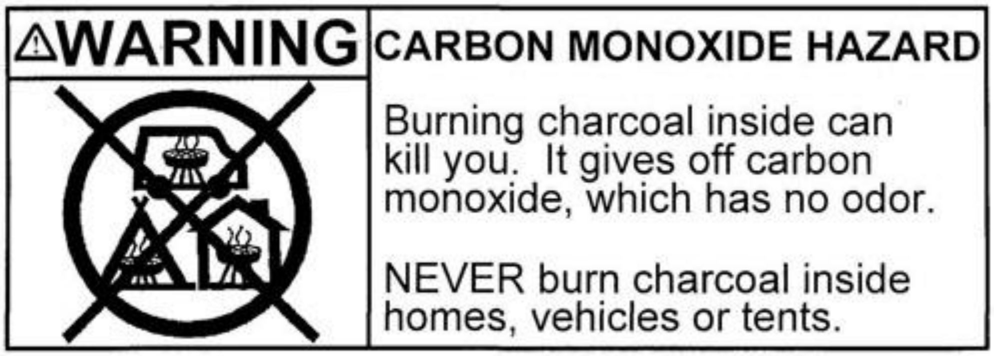
Table 4.1 ICD-9 and ICD-10 codes used to define a fatal CO poisoning, and the number of deaths identified by ICD-9 and ICD-10 definitions. Overall, 226 deaths were identified by either the ICD-9 or ICD-10 code — 74 by the ICD-9 definition, and 152 by the ICD-10 definition. The 74 deaths identified by the ICD-9 definition are further subdivided by external injury code.

ICD-9 Code	**Description**		**Total Number of Deaths from ICD-9 Definition**
N-986	Toxic effects of CO **and** one of the following external injury codes:		74
	Code	**Description**	**Number of Deaths by Code**
	868.3	CO from incomplete combustion of other domestic fuels	25
	868.8	CO from other sources	7
	868.9	Unspecified CO	42
ICD-10 Code	**Description**		**Total Number of Deaths from ICD-10 Definition**
X47 and T58	Poisoning by accidental exposure to gases or vapors **and** toxic effects of CO		152

Table 4.2 Percentage of fatal CO poisonings due to winter precipitation related power outages by sex, age group, ethnicity, place of death, and educational attainment for the U.S., 1984–2004.

Characteristic	Percentage
Sex	
Male	73.5
Female	26.5
Age	
Under 5 years	1.8
5 to 14 years	4.0
15 to 24 years	8.8
25 to 34 years	13.3
35 to 44 years	17.7
45 to 54 years	12.4
55 to 64 years	14.2
65 and older	27.9
Ethnicity	
White, non-Hispanic	70.6
Black, non-Hispanic	17.1
Other, non-Hispanic	3.8
Hispanic	8.5
Place of Death	
Farm	0.7
Home	80.7
Industrial	1.3
Recreation/Sport	0.7
Residential Institution	0.7
Street/Highway	5.3
Business	10.7
Educational Attainment	
No Formal Education	2.1
1-4 years	1.5
5-8 years	13.4
Some High School	13.4
Completed High School	47.4
Some College	12.4
Bachelor's Degree	6.2
Post-Graduate Study	3.6

a)



b)

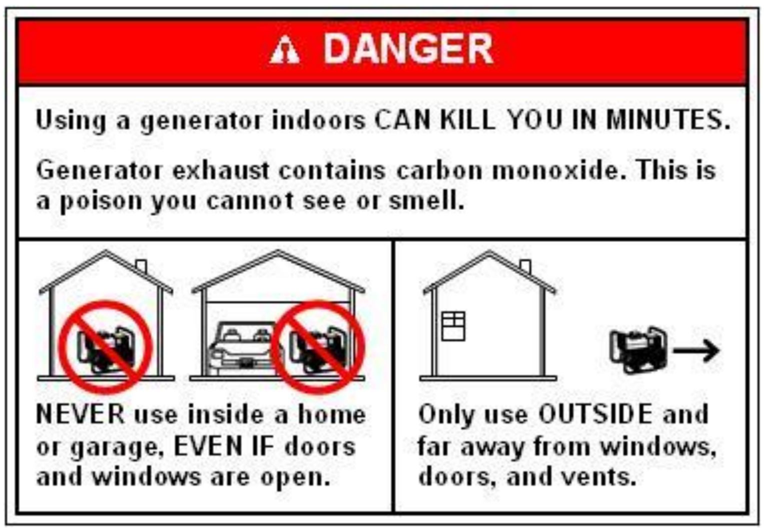


Fig. 4.1 Pictorial warning labels used to warn of CO poisoning due to improper use of a) charcoal b) generators from the U.S. Consumer Product Safety Commission. (U.S. CPSC 2015; U.S. CPSC 2007).

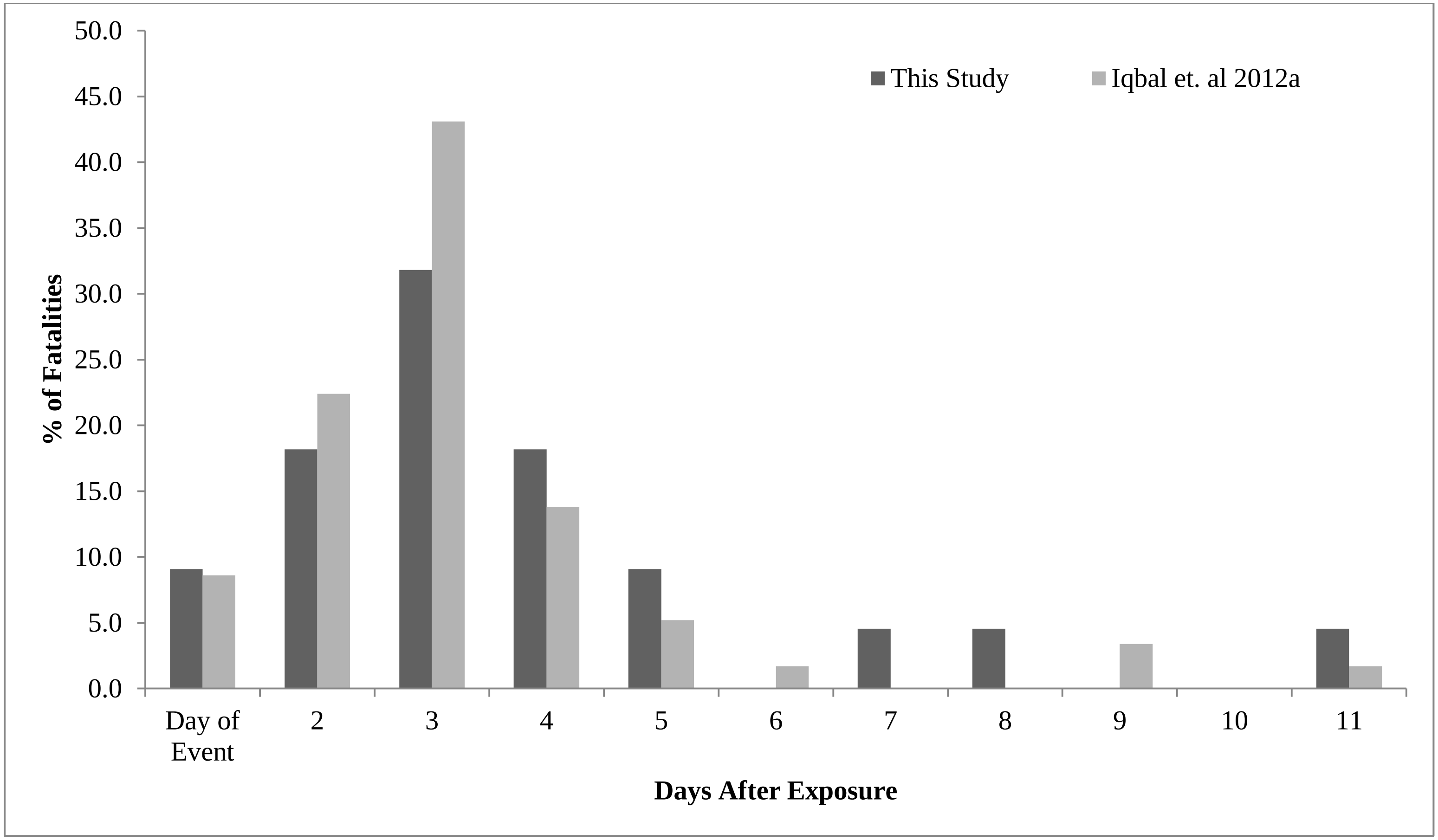


Fig. 4.2 Percentage of fatal disaster related CO poisonings by day after disaster onset based on data collected by Iqbal et. al (2012a) (light bars), and percentage of fatal winter precipitation power outage related CO poisonings by day after disaster onset for the years 1984–1988 (dark bars).

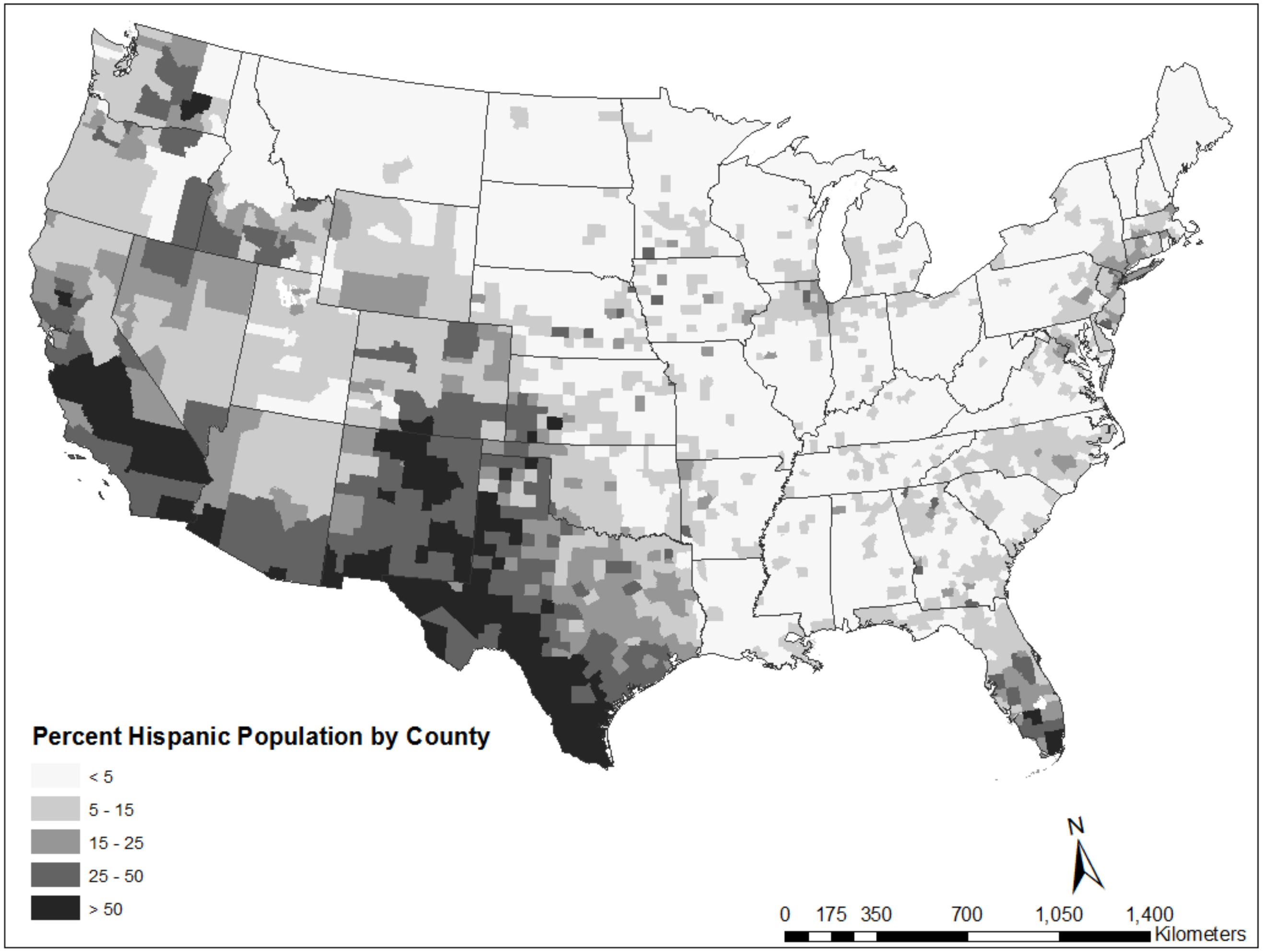


Fig. 4.3 Percentage of Hispanic population by county based on 2013 U.S. census estimates.

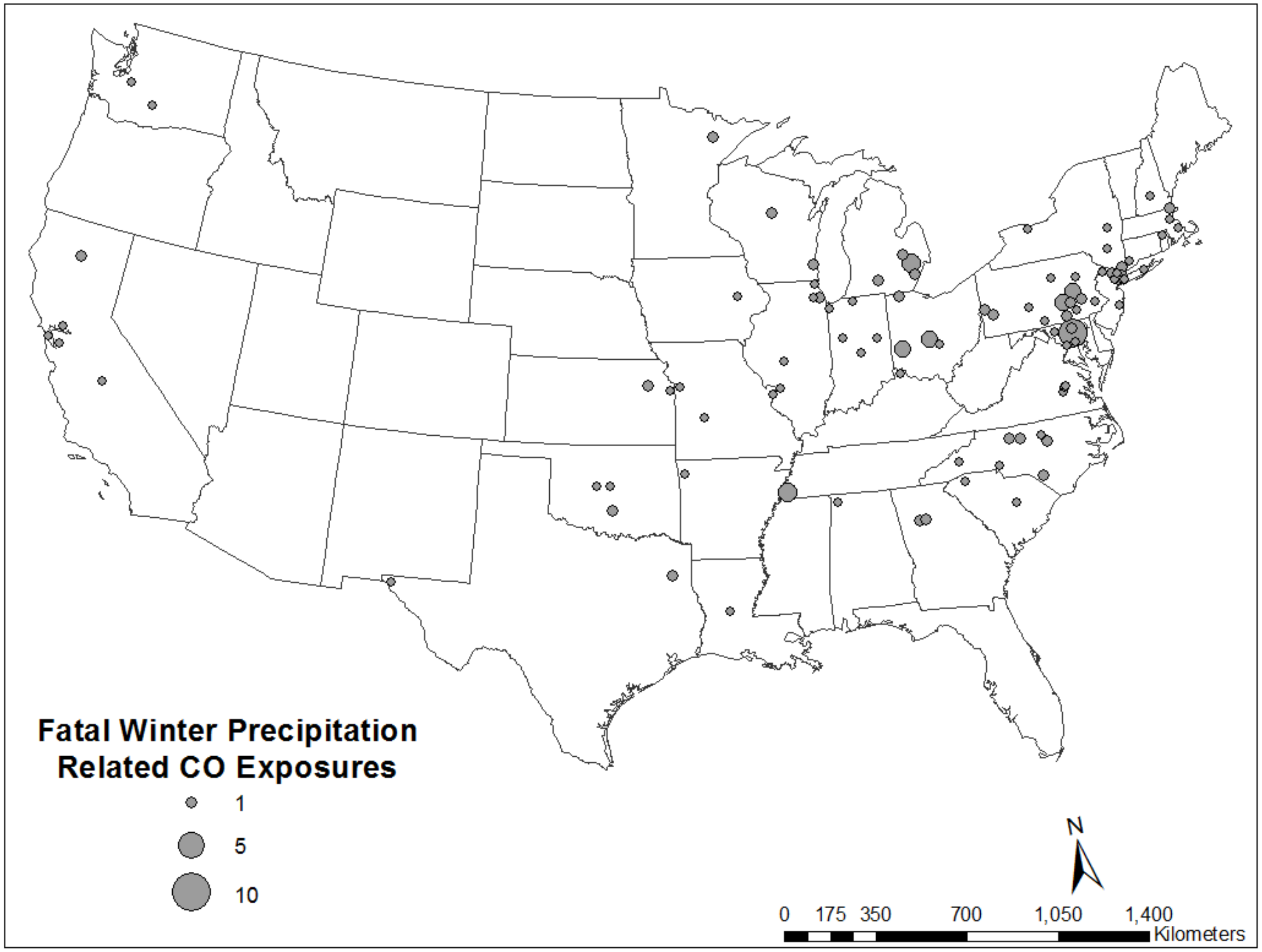


Fig. 4.4 Location of fatal CO poisonings related to winter weather caused power outages, 1984-2004.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 Overview

Winter precipitation is responsible for millions of dollars of economic losses per year and a significant number of fatalities. However, many of these fatalities are due to indirect causes—where the winter precipitation leads to a circumstance that causes a death. As deaths from indirect causes are not included in *Storm Data*, previous studies of winter precipitation mortality have only considered the direct fatalities. This results in an incomplete picture of the losses caused by winter precipitation. This dissertation examines fatalities due to two types of indirect causes related to winter precipitation—vehicle crashes and CO poisonings.

There were several specific goals of this dissertation. The first goal was to examine fatalities that resulted from aircraft and motor vehicle crashes, explore vulnerability to these crashes, and compare the number of fatalities due to these event to other hazards (Chapter 2). The second goal was to evaluate how the presence of winter precipitation affects crash risk as compared to dry conditions, and to examine the contribution of meteorological factors such as intensity of precipitation and precipitation type to overall crash risk (Chapter 3). Finally, the third goal was to examine deaths due to power outages caused by winter precipitation, examine the demographic characteristics of the victims, and explore the spatial distribution of the fatalities (Chapter 4). The following is a summary of the major findings in this dissertation.

5.2 Summary

a. Winter precipitation related vehicle crashes

Chapter 2 considered vehicle fatalities caused by winter precipitation. Between 1975 and 2011, winter precipitation was a factor in nearly 28,000 aviation and motor vehicle accidents which resulted in over 32,000 fatalities, an average of nearly 900 fatalities per year. While this study found over 13,000 transportation fatalities which involved winter precipitation during the 1996–2011 period, *Storm Data* only contained 571 winter precipitation related fatalities from any cause, as vehicle fatalities are considered to be indirect and therefore not officially counted in *Storm Data*. Fatality totals from winter precipitation related vehicle accidents far eclipse fatality totals from other, more prominent weather hazards such as tornadoes, flooding, and hurricanes. For example, from 1996–2011, winter precipitation killed an average of 866 people per year, while tornadoes killed 92 per year. While there are many factors that can lead to a fatal winter precipitation related vehicle crash, the meteorological community plays an important role through forecasting winter precipitation and through communication of the risk of winter precipitation to the public. This work is important as it is among the first to explore the temporal trends, spatial distribution, and excess mortality due to winter related vehicle crashes.

The number of motor vehicle fatalities involving winter precipitation showed a decreasing trend during the period; however the annual percentage of motor vehicle fatalities attributable to winter weather has remained nearly constant through the study period. The decrease in motor vehicle fatalities related to winter precipitation is proportional to the overall decrease in all motor vehicle fatalities, and it is likely that the decrease in winter precipitation related deaths is the result of improvements in vehicle and roadway safety that have led to a decline in all motor vehicle fatalities, including those which are related to winter weather.

Most fatal motor vehicle crashes involving winter precipitation occur during the daylight hours, while fatal crashes involving other weather conditions are more prevalent at night. Age-adjusted standardized mortality ratios reveal significant clusters of increased mortality in the western U.S. and areas of New York and Pennsylvania, while several urban and Gulf Coast locations had clusters of lower than expected mortality. More interesting are the High-Low (indicating areas with high SMR surrounded by areas with low SMR) located mostly in the eastern U.S. and Ohio River Valley, and Low-High (indicating areas with low SMR surrounded by areas with high SMR) clusters found in the western United States.

Aviation fatalities also followed a declining trend, most likely due to improvement in de-icing procedures and cockpit communications after the Air Florida disaster in 1982. The spatial distribution of fatal winter precipitation related aviation crashes was very different than that of vehicle collisions. Fatal aviation crashes were most common in the western U.S., where winter precipitation can obscure mountaintops or rising terrain and where high terrain can make it difficult for pilots to recover from a loss of situational awareness when precipitation is encountered.

b. Risk of crash during winter precipitation

A number of environmental factors, including winter precipitation, can affect the likelihood of driver error and crash. In Chapter 3, a matched-pair analysis was used to pair hours with winter precipitation to control hours that were dry in order to compare automobile crashes, injuries, and fatalities between events and controls in 13 U.S. cities. The primary finding is that winter precipitation leads to a 19% increase in crash risk and a 13% increase in injury risk as compared to dry conditions, with no significant difference in the relative risk of fatality. Spatially, the highest relative risk of crash is found across the lower Missouri River and Ohio River valleys. The spatial pattern of the relative risk of injury is similar to that of crash, but with elevated relative risk extending in to the southeast U.S. While 13 cities is not a sufficient sample to determine the spatial pattern of risk across the entire U.S., these results do suggest there is a spatial component of the relative risk of crash and injury during winter precipitation.

Examining relative risk due to precipitation type, time of day, intensity, and first events showed that no single factor was a consistent predictor of the relative risk of crash or injury. The most reliable predictor was intensity, with 12 out of 13 cities showing an increased relative risk of crash and 9 out of 13 cities showing an increased relative risk of injury during heavier precipitation. Overall, the relative risk of both crash and injury were significantly higher during heavier precipitation. Time of day was the second most reliable predictor, with 11 out of 13 cities experiencing their greatest relative risk during the afternoon (1200-1759 local time) and evening (1800-2359 local time) periods, with the evening period exhibiting significantly higher relative risk of crash than the other six hour periods. In an unexpected finding, no significant difference was found in the relative risk of crash or injury between snowfall events and ice precipitation, although both precipitation types led to an increase in crash risk as compared to dry periods. Finally, the relative risk of crash and injury were higher during the first three winter precipitation events of the year as compared to subsequent events, but the difference was not statistically significant. In contrast with Eisenberg and Warner (2005), no significant difference was found in the relative risk of fatal crash between first precipitation and subsequent precipitation events.

In contrast with the findings of Andrey (2010) that showed little trend in the relative risk of crash during winter precipitation in Canada, this study found a significant downward trend in the relative risk of both crash and injury during winter precipitation. When combined with the overall downward trend in all types of crashes, this results in a 40% decline in crashes and a 53% decline in injuries per 100 million VMT during winter precipitation. Despite the decline in relative risk during the period, relative risk continues to be elevated during winter precipitation as compared to dry weather.

c. CO poisonings due to winter precipitation related power outage

Chapter 4 considers fatal CO poisonings due to power loss caused by winter precipitation by combining data on electrical loss, major snowstorms, and deaths due to unintentional non-fire related CO exposure. Many previous studies have examined CO poisonings related to specific winter precipitation events, however, this study is the first to examine deaths related to winter weather across the entire U.S.

Overall, there were 226 deaths due to winter weather power outage related CO poisonings during the 1984–2004 period, an average of 10.8 per year. Comparison of the period 1994–2004 to previous studies reveals that winter weather related power outages are responsible for nearly 6% of unintentional non-fire related CO poisoning deaths, nearly 20 times what was found by Iqbal et al. (2012a). These results show that winter precipitation related power outages are a risk to public health, and that the risk may be greater than previously estimated.

Many of the results of this study are consistent with previous case studies of winter precipitation related CO poisoning, indicating that those findings are generalizable beyond specific cases. Deaths were most common among men and those aged 65 or older, similar to other studies of disaster related CO poisoning and unintentional non-fire related CO poisonings overall (Iqbal et al. 2012a; CDC 2007). However, significant differences were found in terms of ethnicity between this and previous studies of disaster related poisonings. Examination of the educational attainment of victims revealed that nearly 80% of victims had a high school education or less.

Another important contribution of this study is the examination of the spatial patterns of fatal CO poisonings related to power outages caused by winter weather. A unique distribution is found, with most fatalities in the mid-Atlantic, and few fatalities found in the states that typically see the highest death rates from CO poisonings. Further, around 20% of the U.S. population lives in rural areas, but 29% of deaths occur in rural areas.

5.3 Conclusions

While researchers know that winter precipitation can result in fatalities, few studies have addressed these deaths, and those that have do not include deaths due to indirect causes. Results from this dissertation show that indirect winter precipitation related motor vehicle fatalities kill significantly more people than most other meteorological hazards, while winter related aviation crashes and CO poisonings kill nearly as many as other prominent hazards such as cold (Table 5.1). Combined, these indirect winter precipitation related events are a significant threat. It is hoped that by identifying the magnitude of the hazard posed by winter weather, this research will initiate efforts to reduce these losses.

The results of this dissertation also reveal several avenues for future research. Analysis of SMR clusters found in this work, in particular the High-Low and Low-High clusters, can identify factors that influence mortality and result in different outcomes as compared to neighboring clusters. It is hoped that once identified, these factors can be used to reduce mortality from winter precipitation automobile crashes across the entire U.S.

Similar to studies of Canadian cities (Andrey et al. 2003), the sensitivity of U.S. cities to winter precipitation varies from city to city in a manner that is not easily explained. Future research will be required to determine which safety interventions are most effective in each city and revise or expand safety programs appropriately. In addition, future research should address aspects of societal vulnerability which would vary on a city-by-city basis and may contribute to the relative risk of crash. Consistent with what was found in Canada (Andrey et al. 2013), there is not a clear link between experience with winter weather and reduction in overall relative risk. It is therefore important to continue research in to the relative risk of crash and injury in the U.S. by exploring additional regions, driver adaptations to winter weather on short time scales (such as reductions in speed), the interactions between weather variables and non-weather elements, and to explore factors such as the importance of weather forecasts and road maintenance to relative risk. It is hoped that these efforts can identify actions that can be applied to reduce the hazard of winter precipitation to motorists.

This study has also revealed the difficulty in gathering data to assess indirect fatalities. Reduction of mortality due to winter precipitation (or any hazard) requires an understanding of all fatalities, both direct and indirect. The author echoes the call of Gall et al. (2009) for an open, comprehensive dataset of hazard losses, which focuses on accurate counts of losses, both direct and indirect, from all hazards. A comprehensive database of all losses will allow researchers and policy makers to better understand hazards such as winter precipitation, and ultimately make decisions that will reduce mortality due to atmospheric hazards.

Table 5.1 Average number of deaths per year due to various meteorological hazards based on 1996–2011 data, except CO poisonings which are based on 1996–2004 data. Results from this study in italics.

Hazard	**Number of Fatalities**
Lightning	41
Tornado	92
Flood	82
Hurricane	77
Direct Winter from Storm Data	36
Wind	49
Heat	144
Cold	27
Rip Currents	39
Winter Related Motor Vehicle	*817*
Winter Related Aviation	*13*
CO Poisonings	*19*

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